Field distribution in the TTF 3 coupler and field enhancement due to the change of Q_{ext} with a 3-stub tuner for different X-FEL operating conditions

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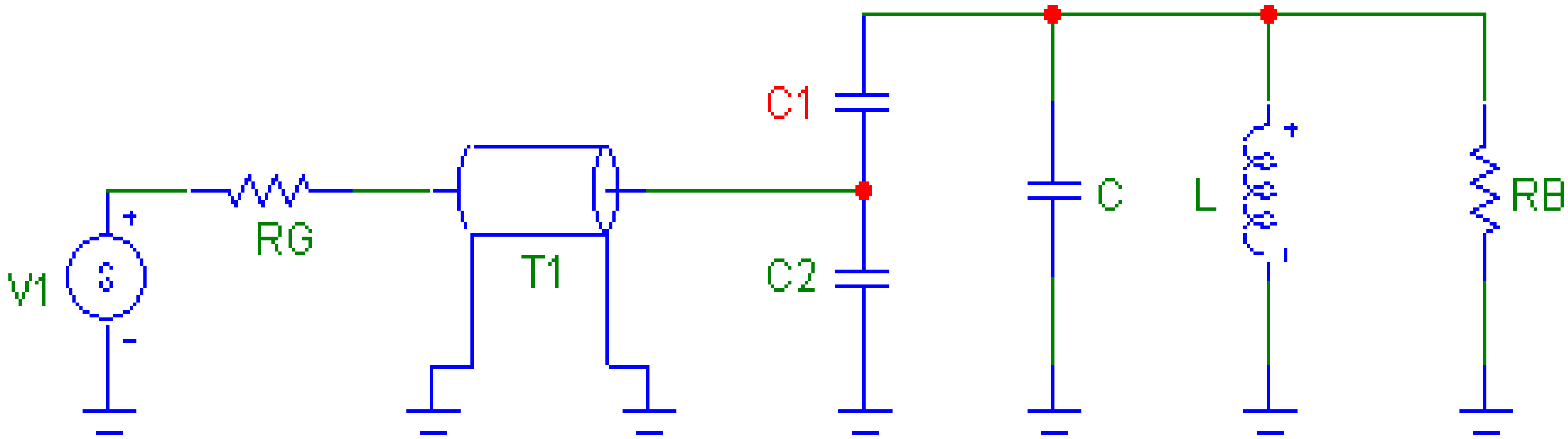
Introduction

I will speak about:

- How behaves the TTF 3 coupler with optimal coupling
- How much the field is enhanced in case of fixed coupler with 3-stub transformer
- What is the range of phase shift of 3-stub transformer

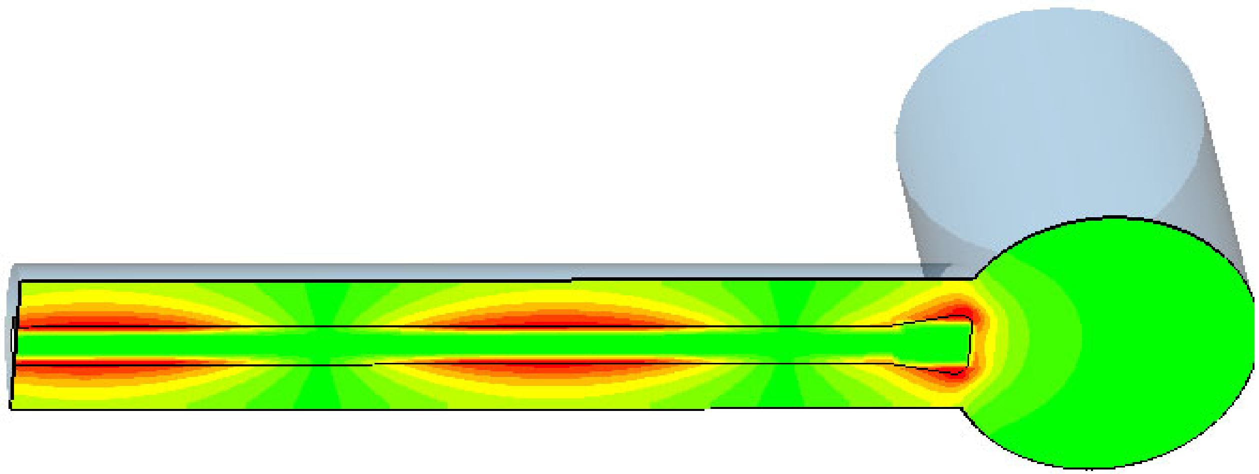
Model of cavity with coupler



RG = generator impedance
C1 = coupling capacity
C2 = capacity of the antenna end
L,C = parameters of parallel resonant circuit
RB = beam load

Model of cavity with coupler - effect of antenna end capacity (C2)

This capacity loads the transmission line and has influence on the reflection coefficient. The following simulation has been done in the CST Microwave Studio for the TTF 3 coupler in the cut-off pipe:



Model of cavity with coupler - effect of antenna end capacity (C2)

We see, that the voltage standing wave maximum is shifted about 30° behind the end of antenna (one half of $\mathrm{Arg}(S_{11})$).

From the	$S_{11} = 1<-57°$
we get	$X_{C2} = 129\ \Omega$ ($Z_0 = 70\ \Omega$)
and	$C2 = 0.95$ pF

The feedback tunes the cavity to resonance (max. electric field) and is not able to compensate the capacitive load by detuning of cavity. In case of critical coupling the load reflection coefficient $|S_{11}| = 0.263$ (7 % of power goes back).

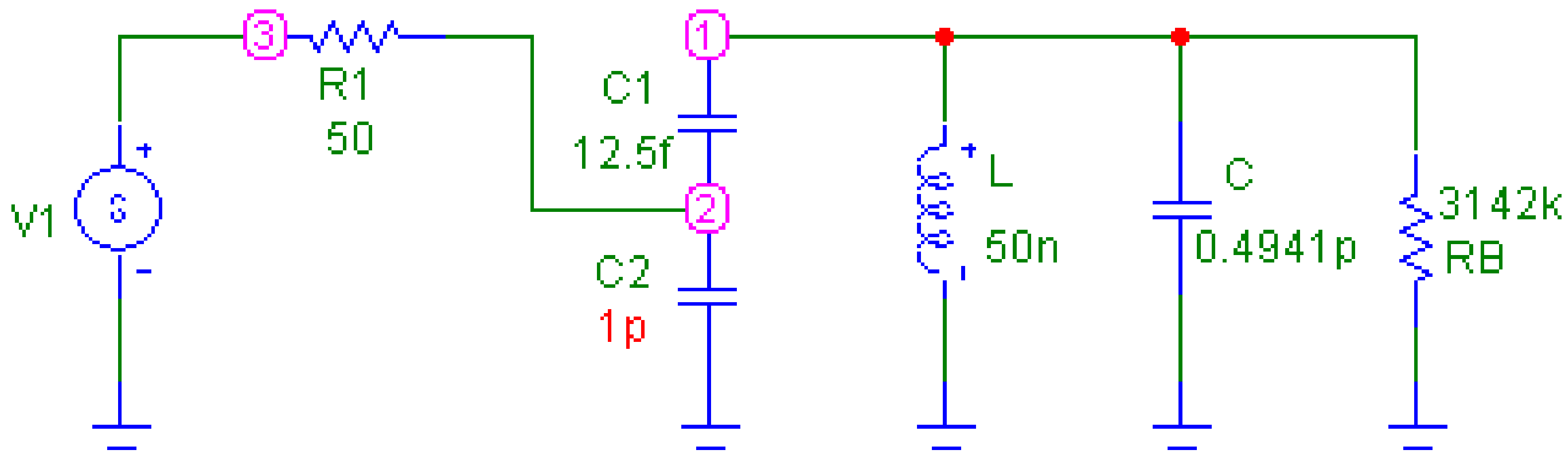
Model of cavity with coupler - effect of antenna end capacity (C2)

Simulation of RLC circuits with Q in order of 10^6 is very difficult. Without loss of generality we can analyze a model of coupler with cavity with lower Q, let's take the following parameters:

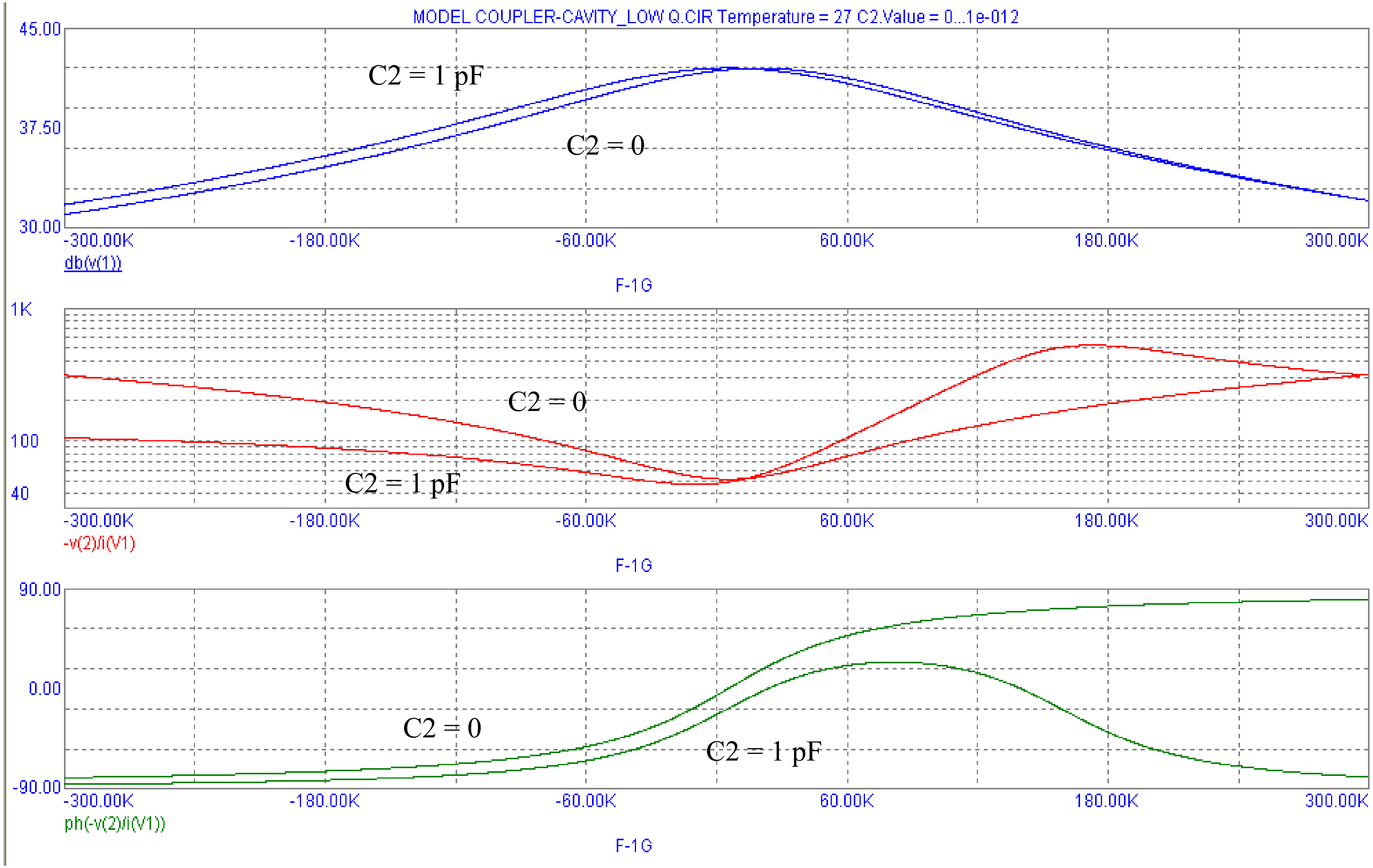
- Q_{ext} of coupler = 10 000
- Characteristic impedance of coupler = 50 Ω
- Capacity of antenna end = 1 pF
- Resonant frequency of loaded cavity = 1GHz

The circuit parameters are adapted to get these properties. The MicroCap 6 is used as a simulation software.

Model of cavity with coupler - effect of antenna end capacity (C2)



Model of cavity with coupler - effect of antenna end capacity (C2)



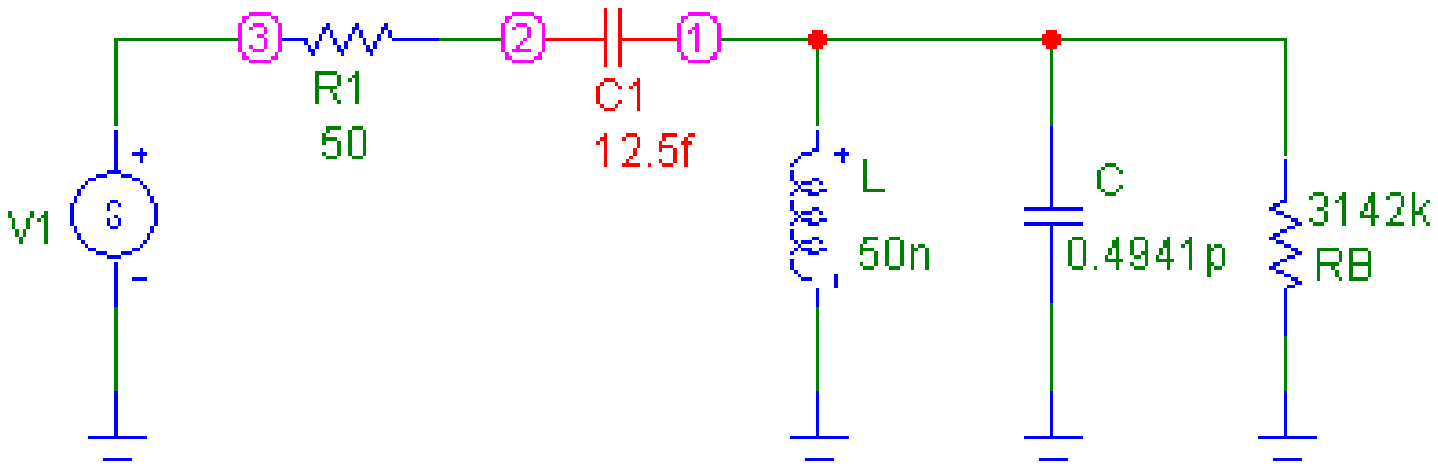
Model of cavity with coupler - effect of antenna end capacity (C2)

The presence of capacitive load of antenna has the following effect:

- The change of cavity resonant frequency is negligible
- In case of absence of load (antenna placed in cut-off) the standing wave maximum is shifted 30° behind the end of antenna
- In case of critical coupling 7 % of power is reflected
- The compensation could be done by inserting a capacitive post into the waveguide in distance $(2n+1).\lambda/4$ from the end of antenna.

AC analysis of the model – standing wave pattern in state of mismatch

Here we will find out whether voltage maximum or minimum is located on the end of antenna in case of absence of beam (strong overcoupling). For this simulation we will neglect the antenna capacity to ground.



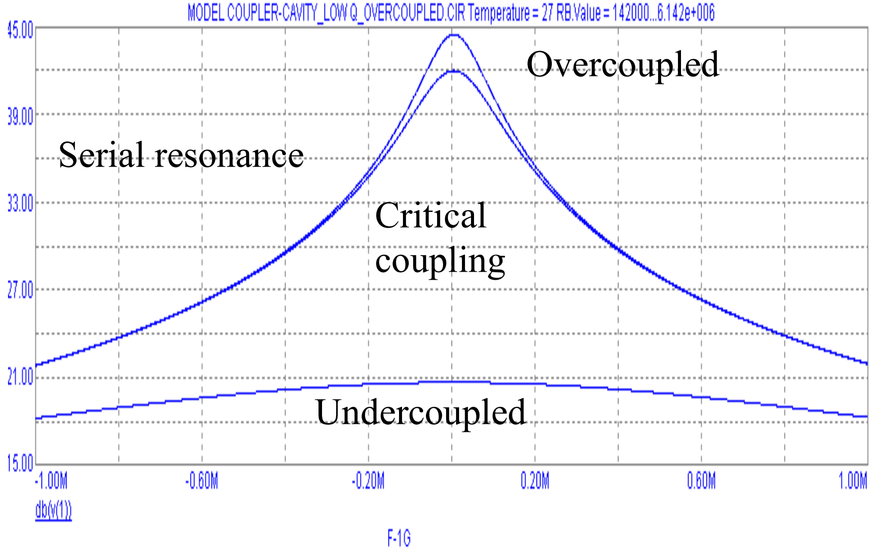
AC analysis of the model – standing wave pattern in state of mismatch

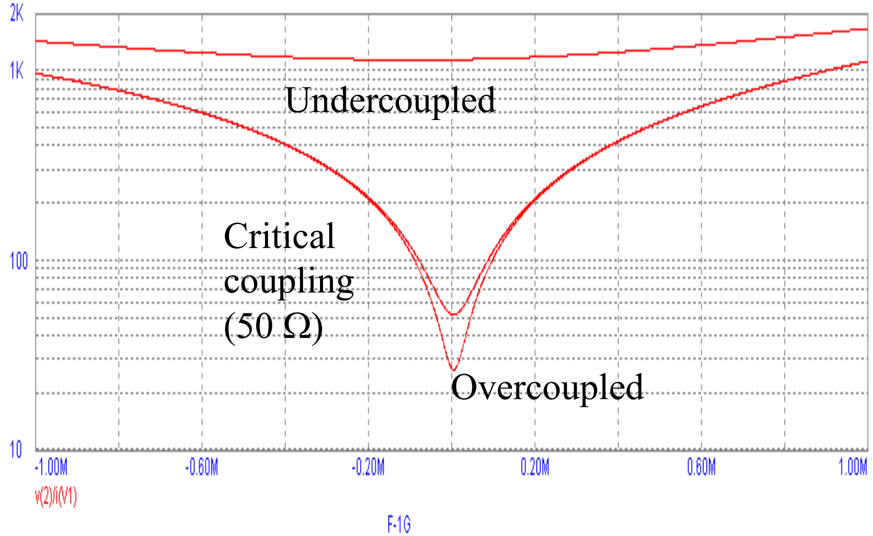
How the model behaves?

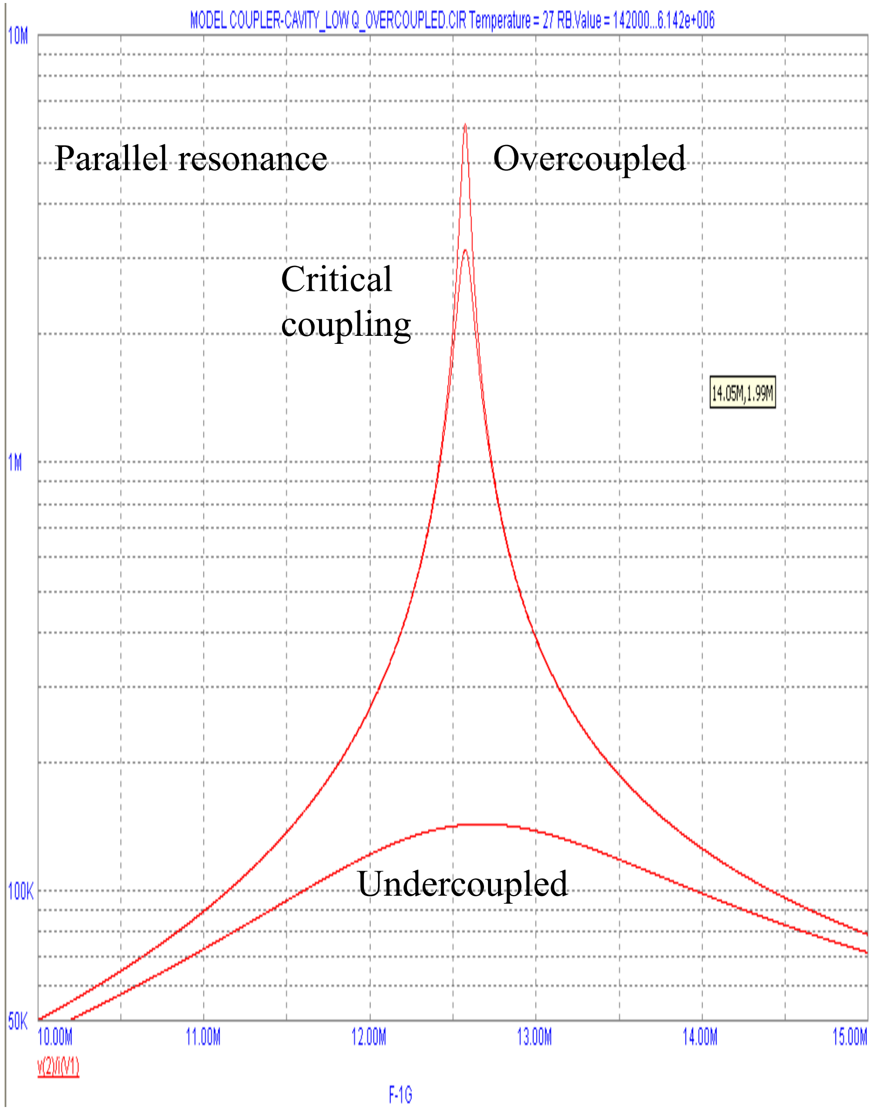
- At the resonance of L and C there is an impedance maximum, but almost no energy transfer to the cavity

- Below this frequency the parallel RLC circuit has inductive character and has a serial resonance with the coupling capacity. Under this condition the impedance (or voltage) on the coupler is low, but the impedance (or voltage) on the parallel RLC circuit (inductance) is very high.

AC analysis of the model – standing wave pattern in state of mismatch







AC analysis of the model – standing wave pattern in state of mismatch

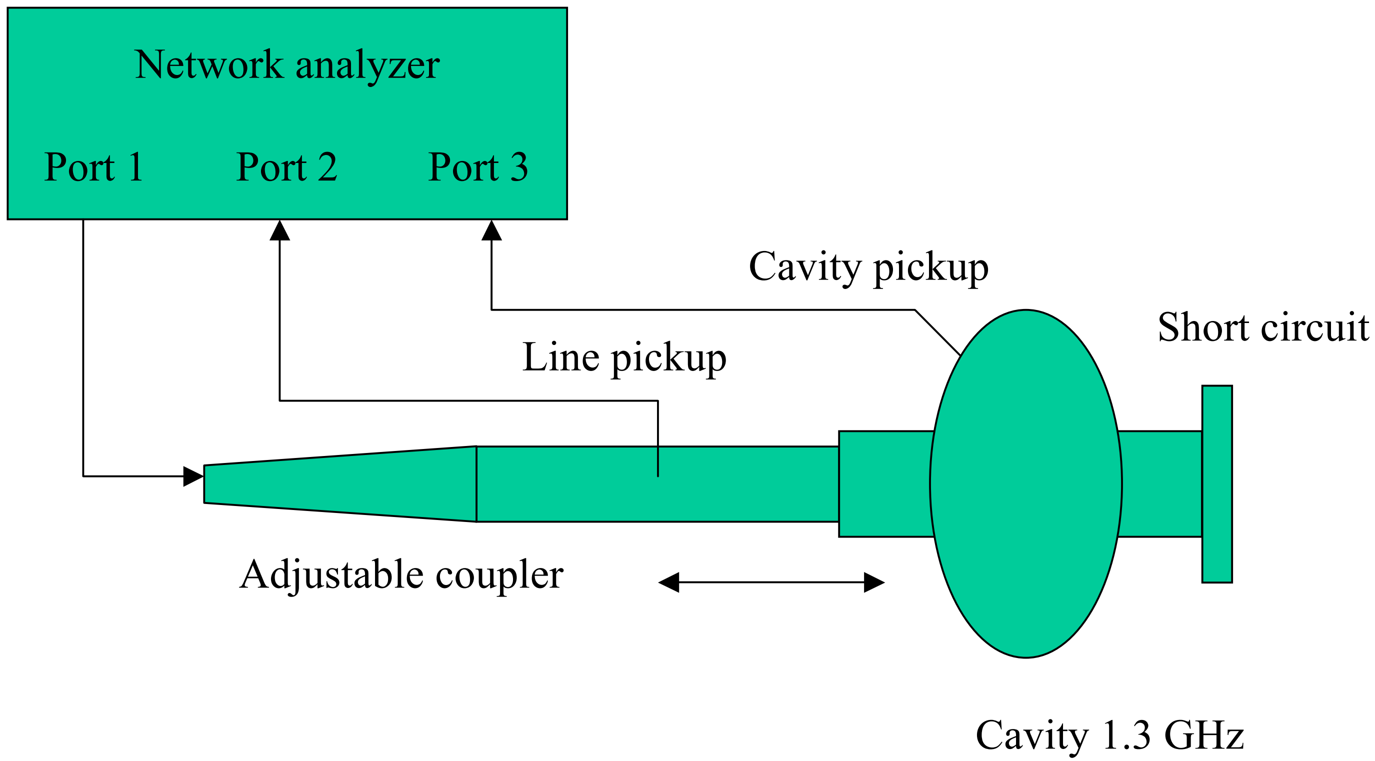
- Parallel resonance of L and C is at f_0 + 12.6 MHz, very high Z_{in}
- Below this frequency the parallel RLC has inductive character
- This inductance resonates with coupling capacity (serial resonance)

  $f = f_0 = 1$ GHz
  - Undercritical coupling: RB = 124 kW, Z_{in} = 1.2 kW
  - Critical coupling: RB = 3124 kW, Z_{in} = 50 W
  - Overcritical coupling: RB = 6124 kW, Z_{in} = 27 W

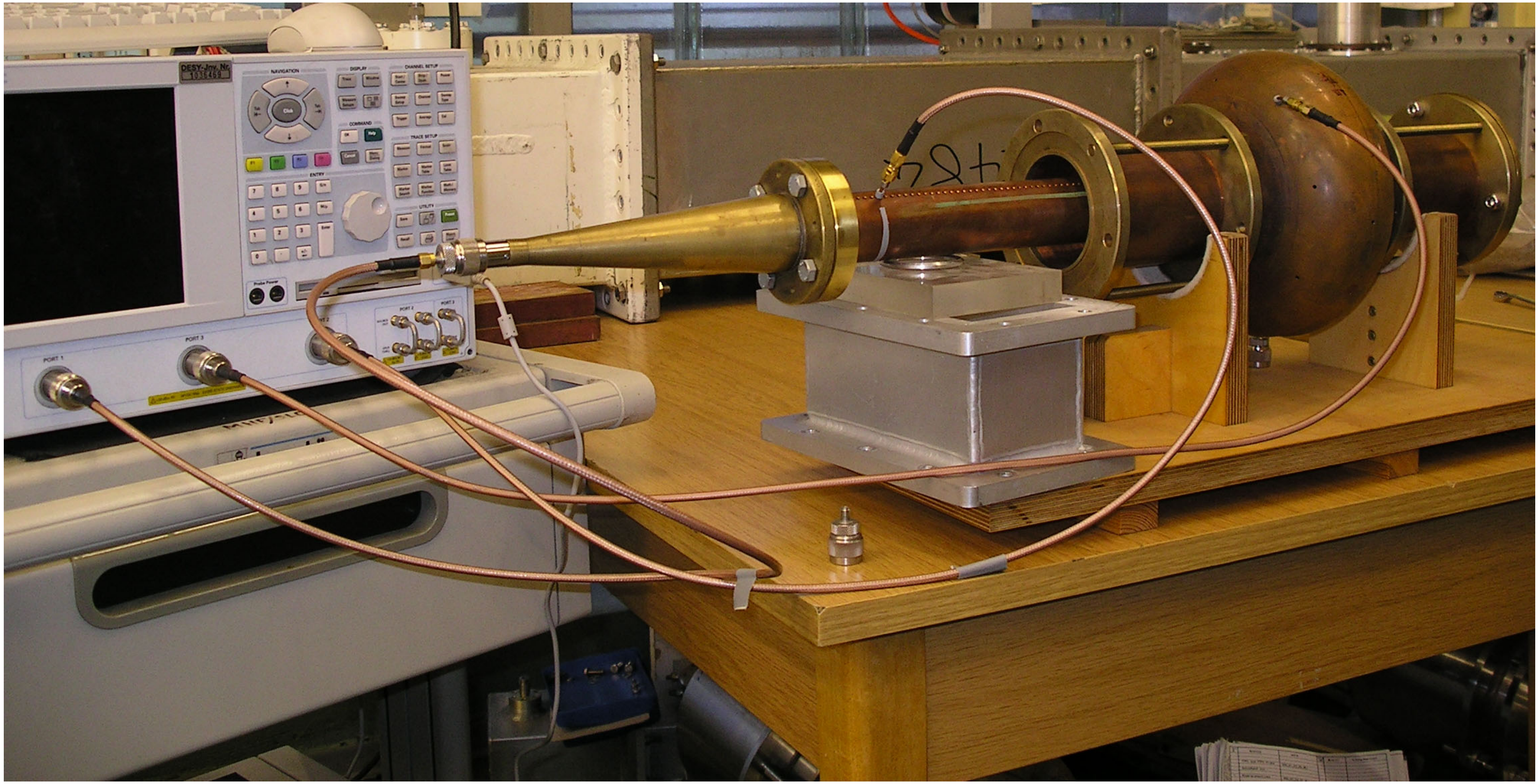
In case of absence of beam the superconducting cavity is strongly overcoupled and the coupler is loaded by extremely low impedance. This means, that the voltage minimum (almost zero) is located on the end of antenna.

Measurement of standing wave pattern

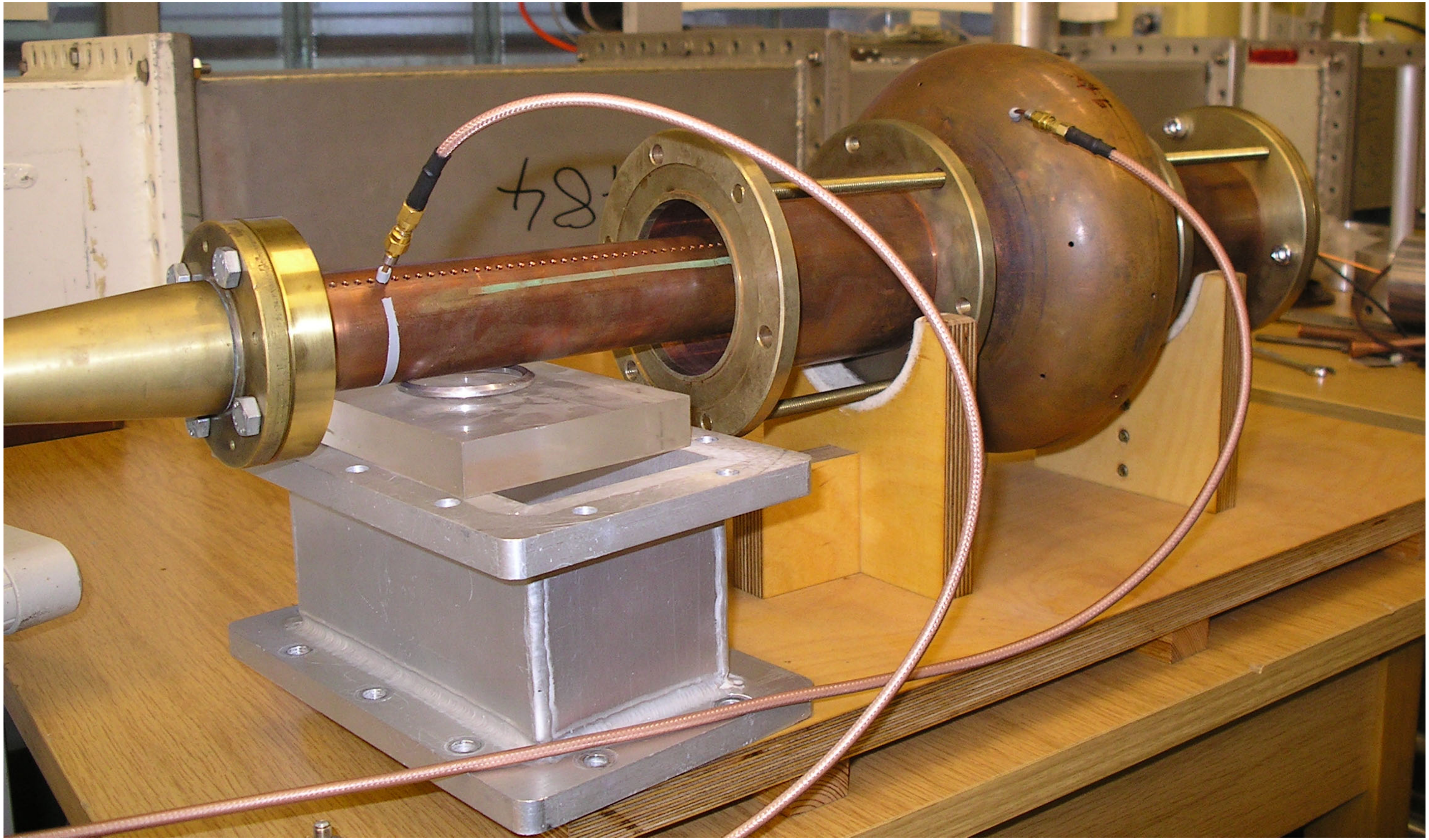
The following experiment has been done to verify the modeling. The line pickup is connected in place of standing wave minimum in case of negligible coupling.



Measurement of standing wave pattern



Measurement of standing wave pattern



Measurement of standing wave pattern

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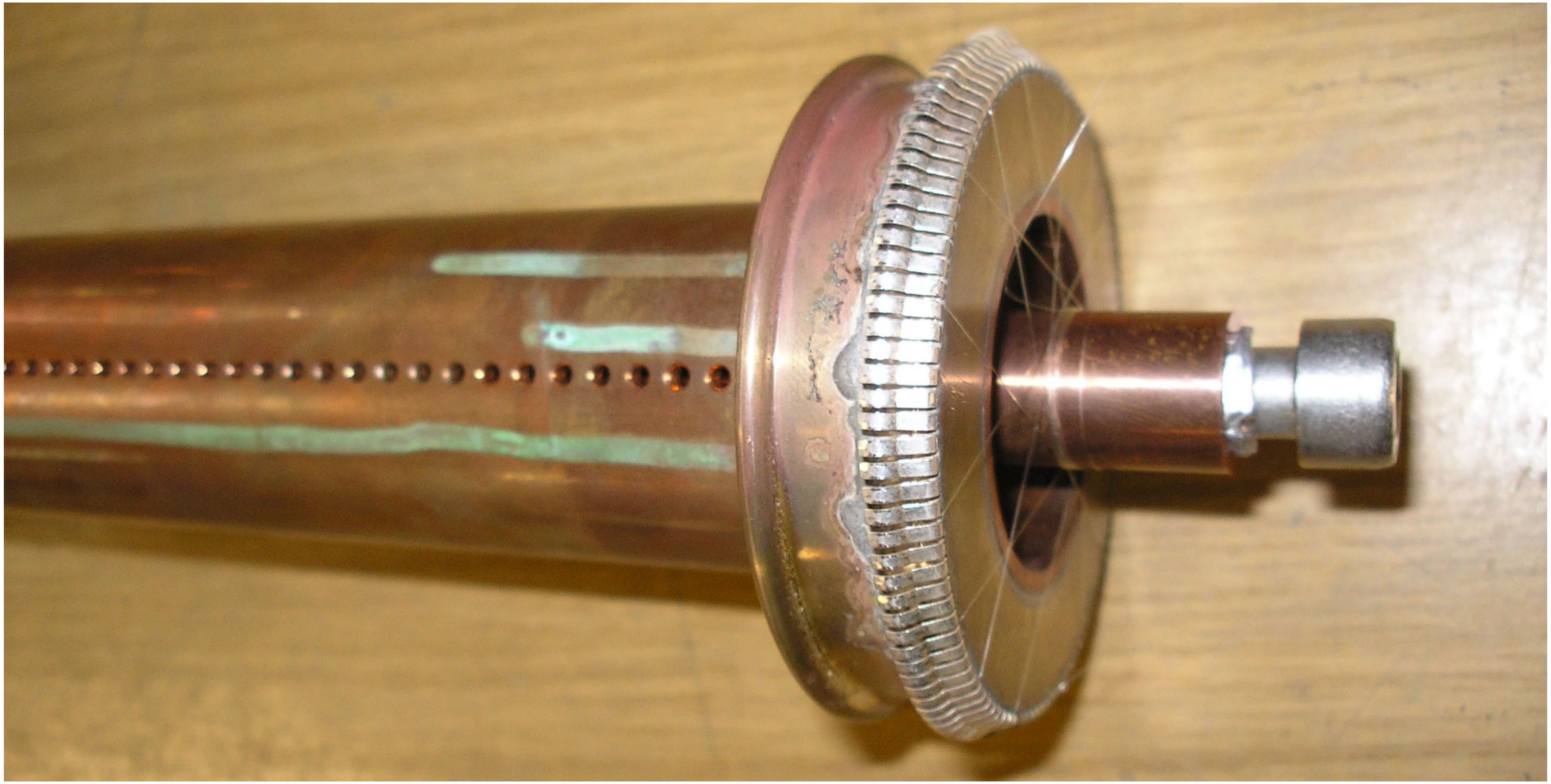
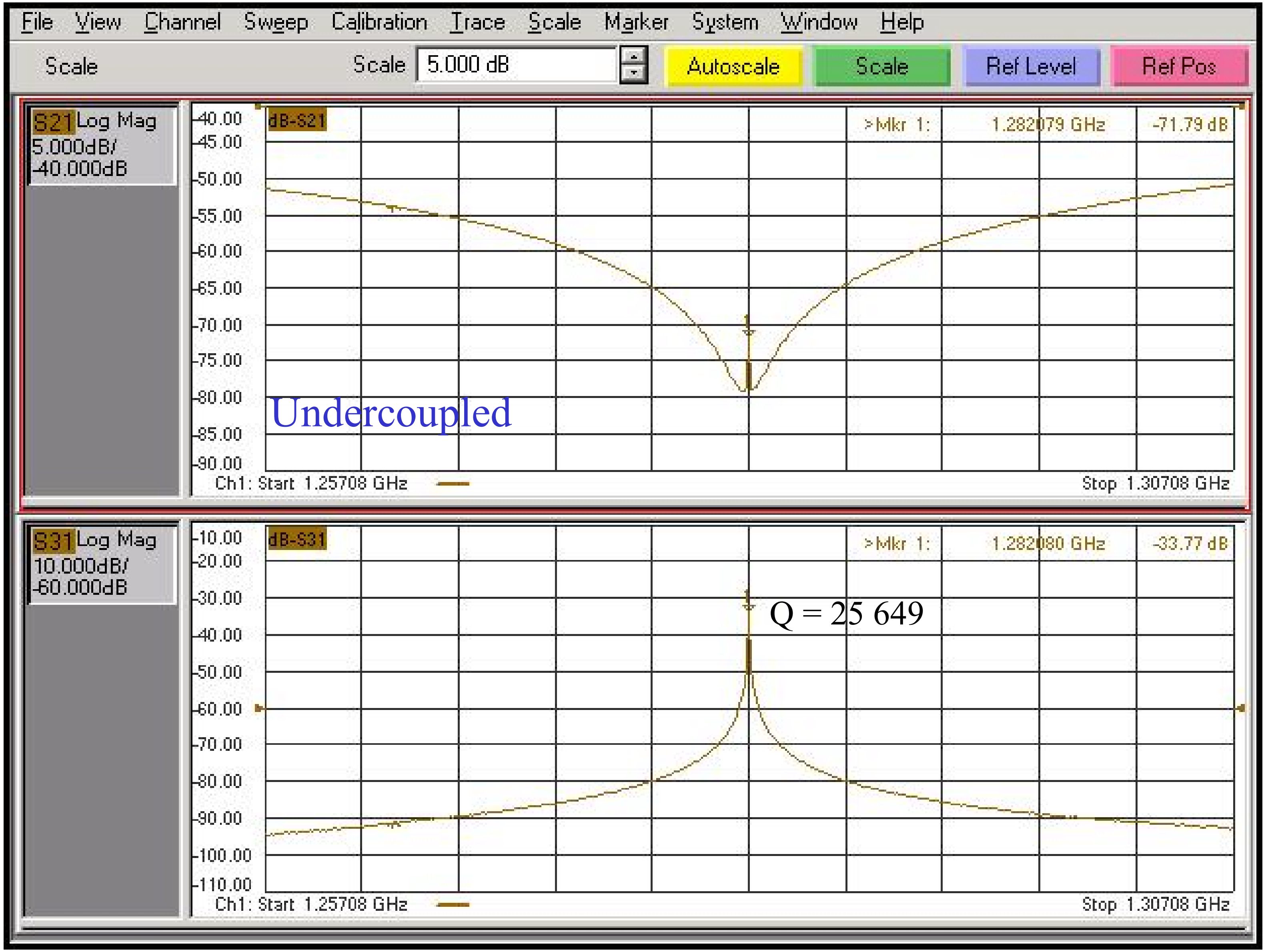
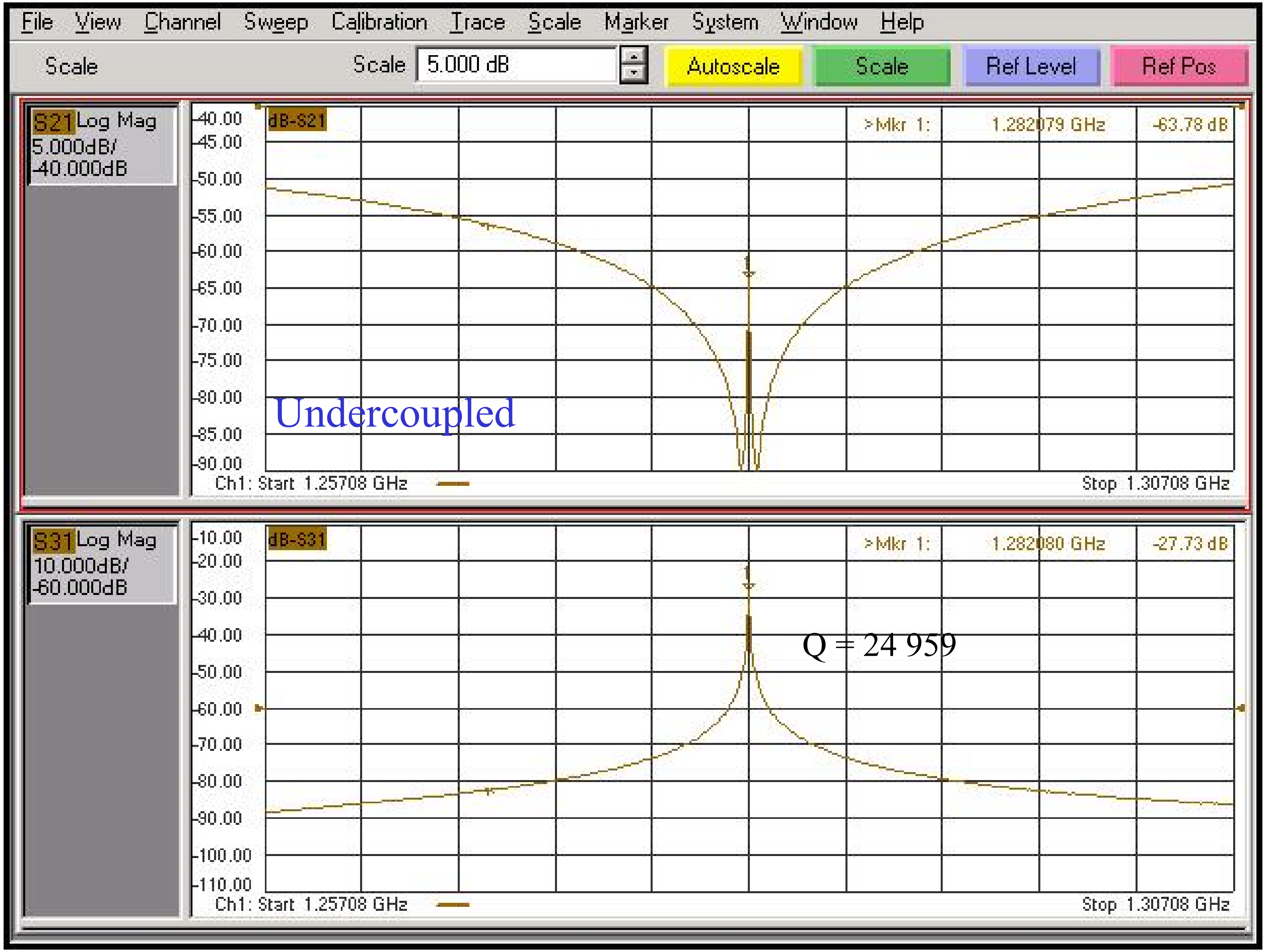


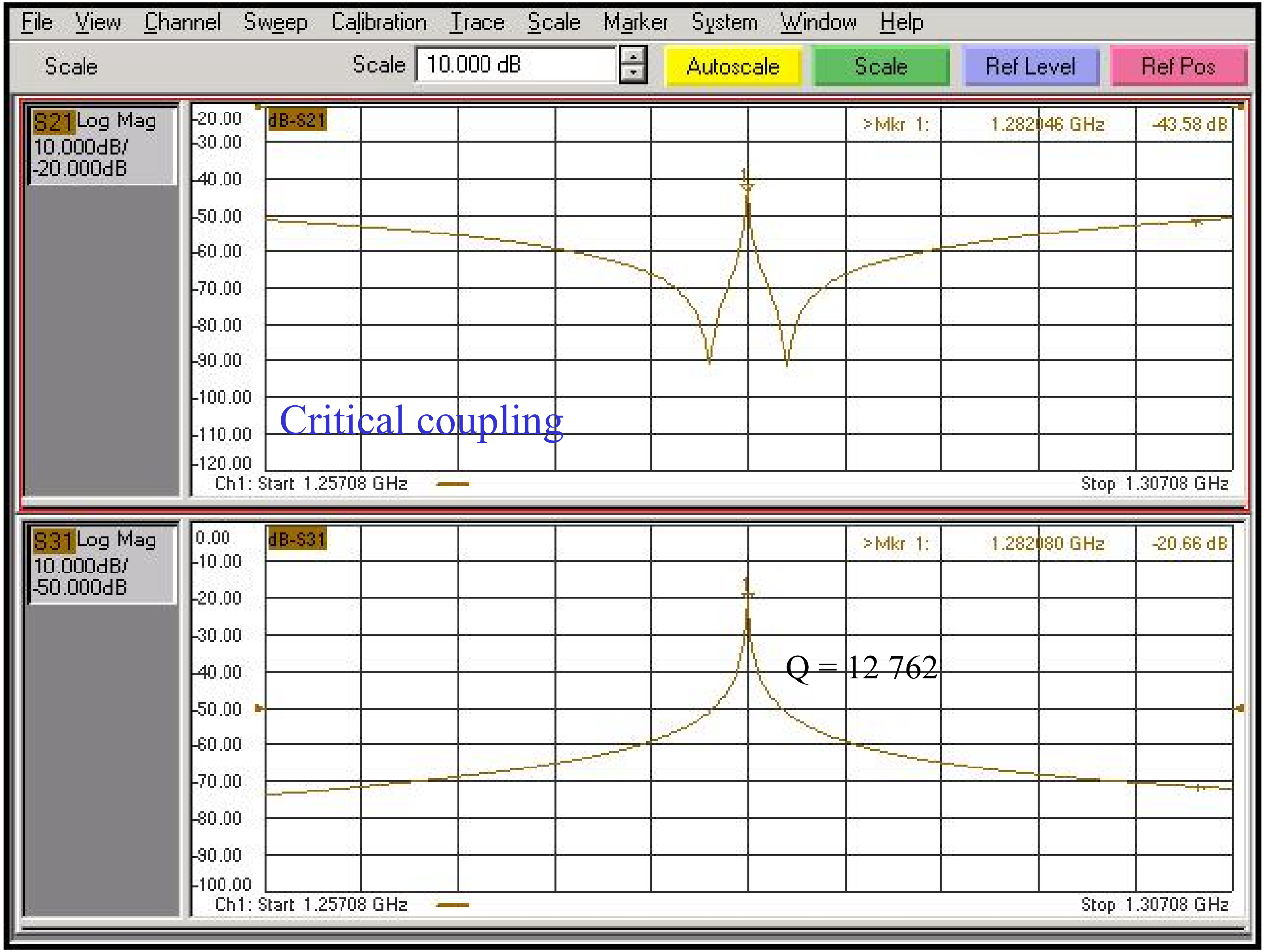
Measurement of standing wave pattern



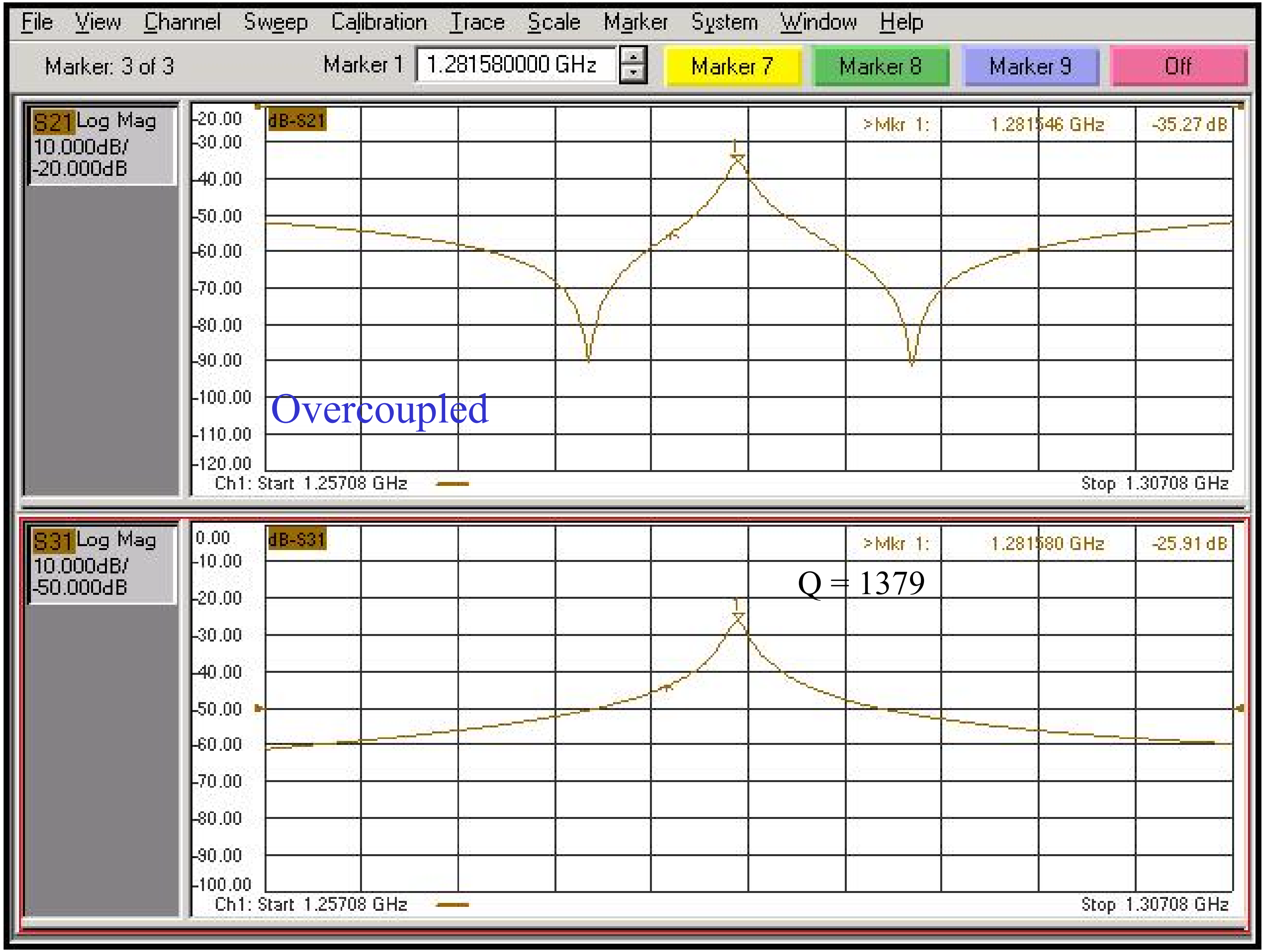
Measurement of standing wave pattern



Measurement of standing wave pattern



Measurement of standing wave pattern



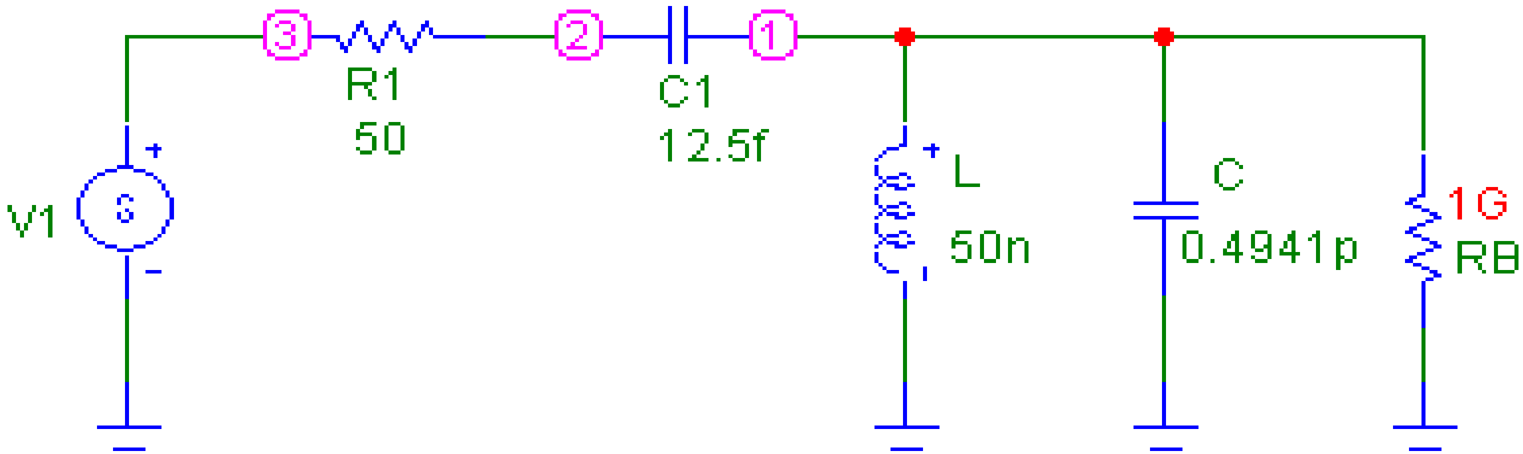
Measurement of standing wave pattern

Results of measurement:

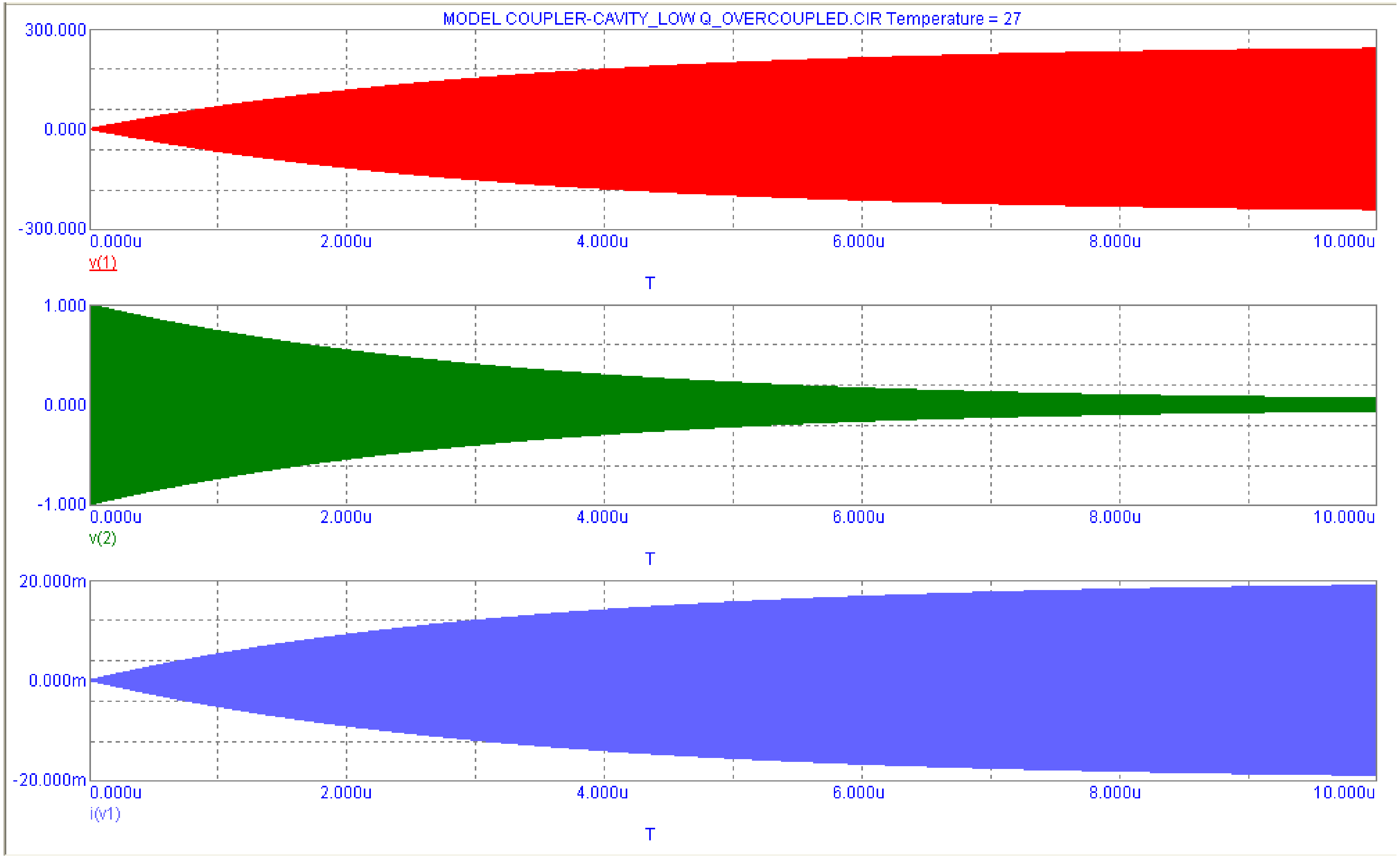
- The line probe is connected to the voltage minimum (negligible coupling) → maximum is on the end (high impegance)
- Increasing of coupling → increasing of probe voltage → decrease of voltage on the end of antenna (decreasing of impedance)
- Case of superconductivity → extremal overcoupling without beam → voltage zero (almost) on the end of antenna

Transient analysis of the model

We will observe the change of impedance on the end of coupler during the transient process of cavity filling in case of overcoupling



Transient analysis of the model

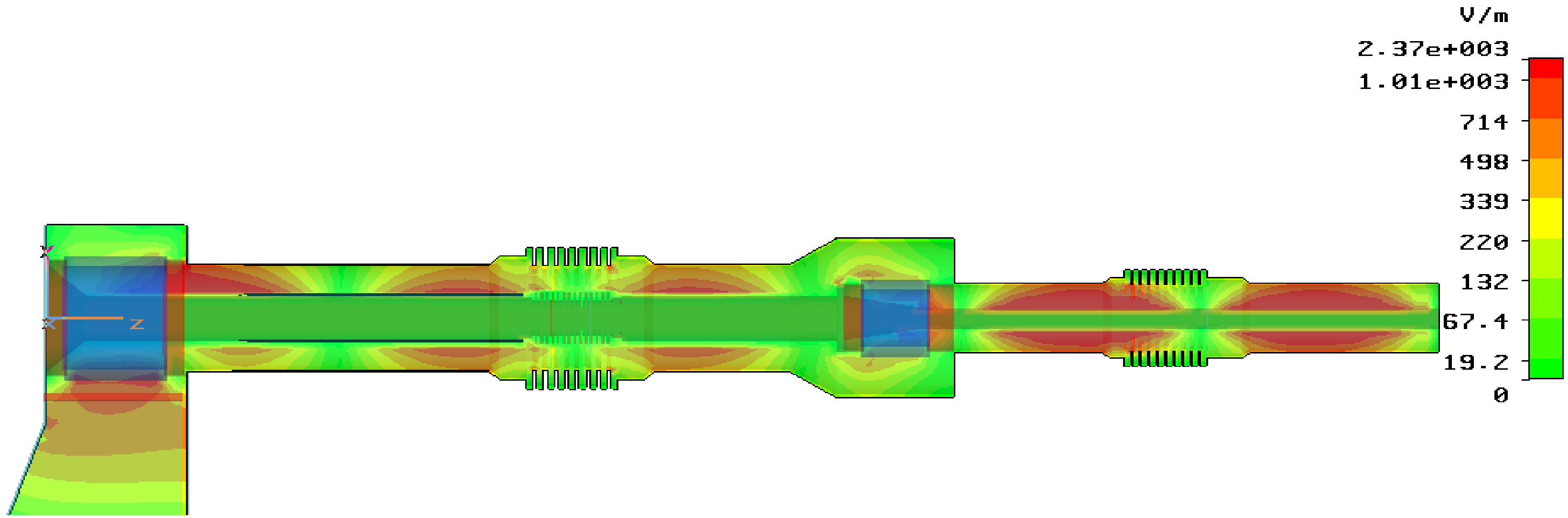


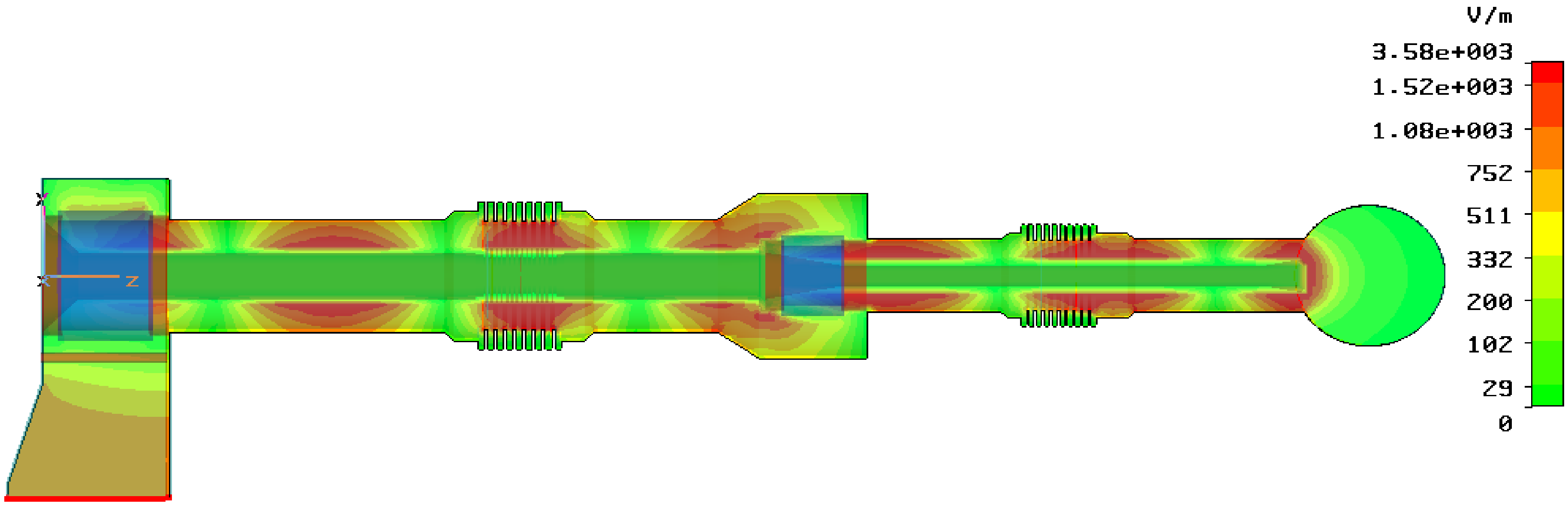
$t = 1\ \mu s : Z_L = 135\ \Omega$ $t = 2\ \mu s : Z_L = 58\ \Omega$ $t = 3\ \mu s : Z_L = 36\ \Omega$

Transient analysis of the model

- During the filling process the analyzed coupler was matched at time $t = 2\mu s$
- Before this time the impedance is high (voltage maximum)
- After this time the impedance is low (voltage minimum)
- It means, that the coupler must be able to operate under both mismatching conditions (open or short on the end)

Simulation of short circuit and cut-off operation of the TTF 3 coupler





Standing wave pattern in coupler - conclusion

- The resonant system coupler - cavity can be analyzed as a serial resonance of coupling capacitor with slightly detuned parallel resonant circuit below the resonance (inductive character)

- The electric field on the end of antenna has maximum in case of undercoupling and minimum in case of overcoupling at resonance frequency

- The capacity between the end of antenna and ground has an influence on standing wave pattern in cut-off operation and cause reflection in case of critical coupling

- During the filling process first is the electric field maximum on the end of antenna, than a moment of matching and after that there is a minimum

- The TTF 3 coupler has an electric field maximum on cold window in case of short-circuit operation (strong overcoupling). The warm window is large and is never in minimum only.

Operation of coupler with fixed antenna and 3 stub tuner – requirements for the XFEL

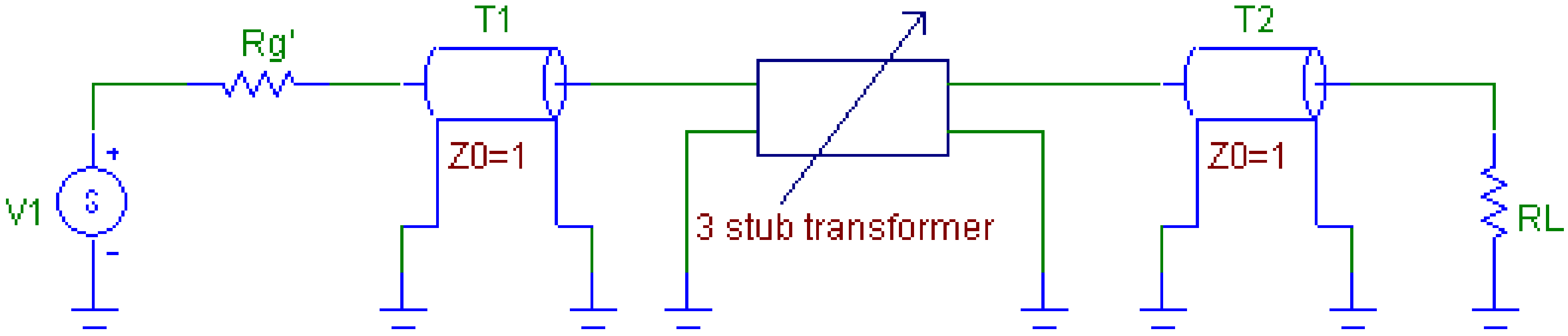
- The TTF 3 coupler is designed for operation with 250 kW pulsed (total reflection) and tested with 1 MW (matched)

- Requirements for the XFEL without energy recovery:
  - Q_{ext} range 2 – $4{,}6.10^6$
  - Beam current 5 mA
  - Input power 120 kW for E_{acc} = 23MV/m at $Q_{ext} = 4{,}6.10^6$
  - Input power 50 kW for E_{acc} = 10 MV/m at $Q_{ext} = 2.10^6$

- Requirements for the XFEL with energy recovery:
  - Input power 30 kW for E_{acc} = 23 MV/m at $Q_{ext} = 4{,}6.10^6$
  - Input power 9,2 kW for E_{acc} = 23 MV/m at $Q_{ext} = 1{,}5.10^7$
  - Input power 5,7 kW for E_{acc} = 10 MV/m at $Q_{ext} = 4{,}6.10^6$
  - Input power 1,7 kW for E_{acc} = 10 MV/m at $Q_{ext} = 1{,}5.10^7$

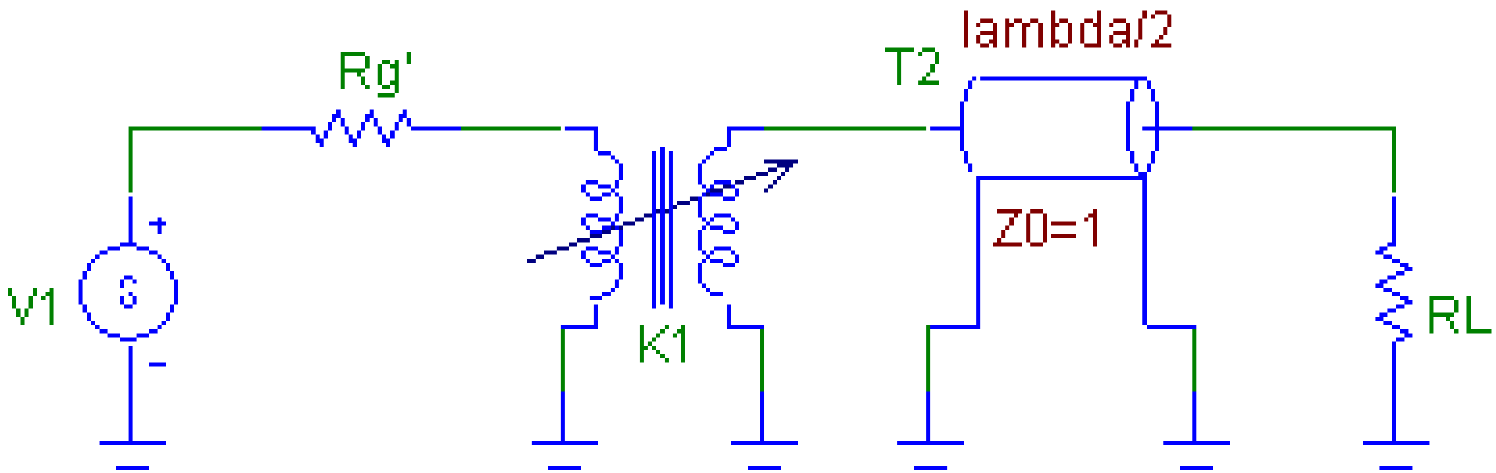
Operation of coupler with fixed antenna and 3 stub tuner - model

We will assume the following model of coupler with 3 stub transformer and cavity at resonance:



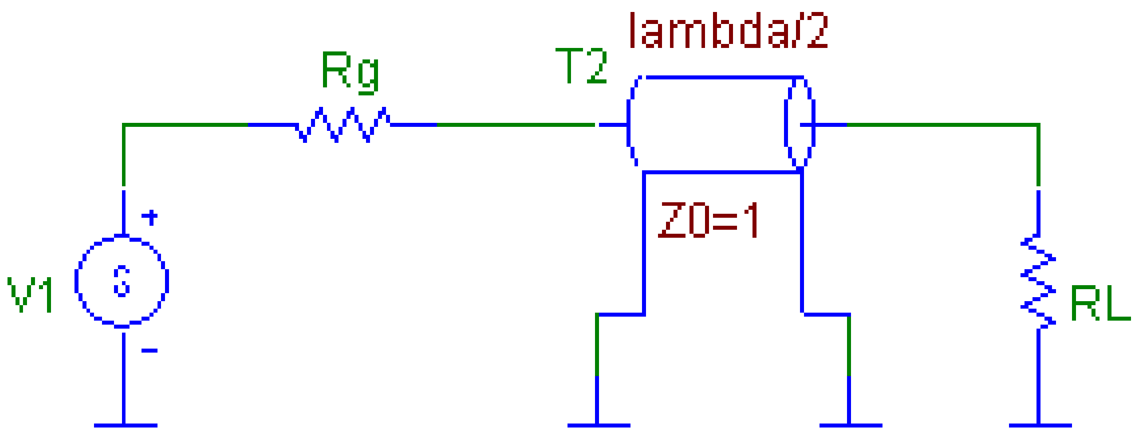
Operation of coupler with fixed antenna and 3 stub tuner - model

The load impedance is real in resonance (if we neglect the capacity of antenna end). The line between the load and transformer rotates the load impedance around the center of Smith chart, so the 3 stub transformer must compensate additional reactance (extend the electrical length of line to n.λ/2) and match the load impedance to generator. We can simplify our model by choosing the length of line equal to λ/2) and replacing the 3 stub tuner by transformer with real transforming ratio:



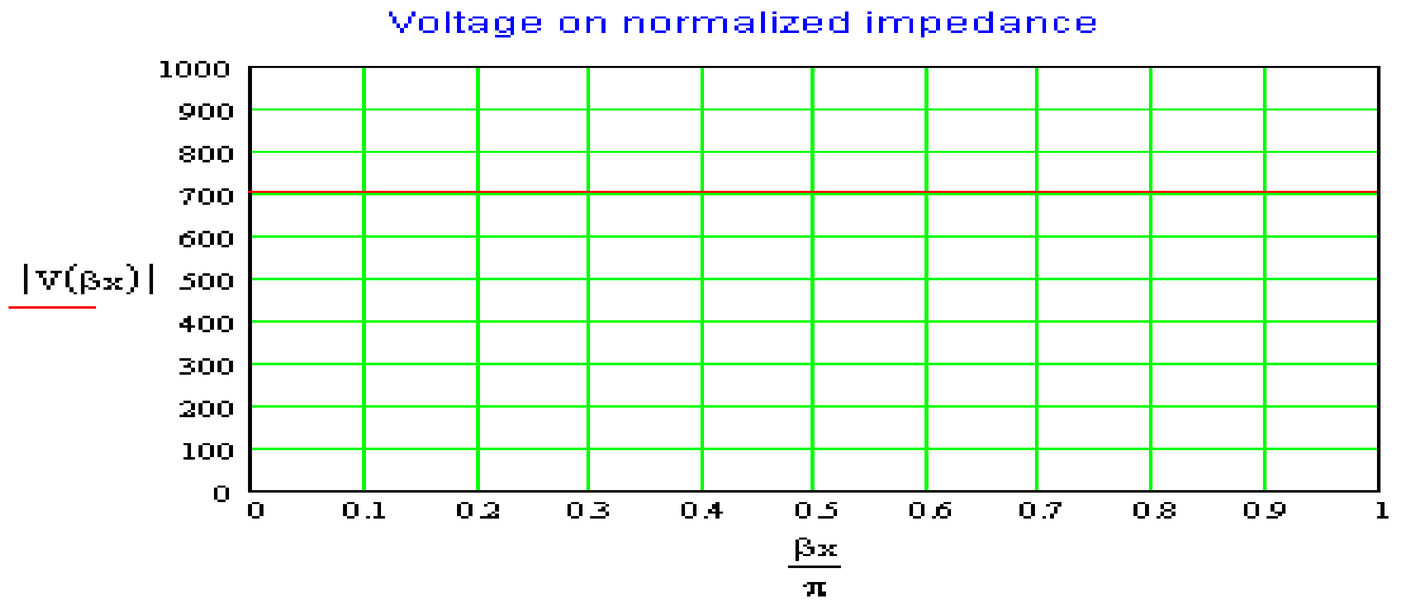
Operation of coupler with fixed antenna and 3 stub tuner - model

The generator impedance with transformer can be replaced by transformed generator impedance. Now we will observe standing waves on the line between generator and load using the Mathcad. The standing wave maxima with 3-stub transformer and appropriate power should not be higher than in case without 3-stub transformer and 250 kW:



Operation of coupler with fixed antenna and 3 stub tuner - model

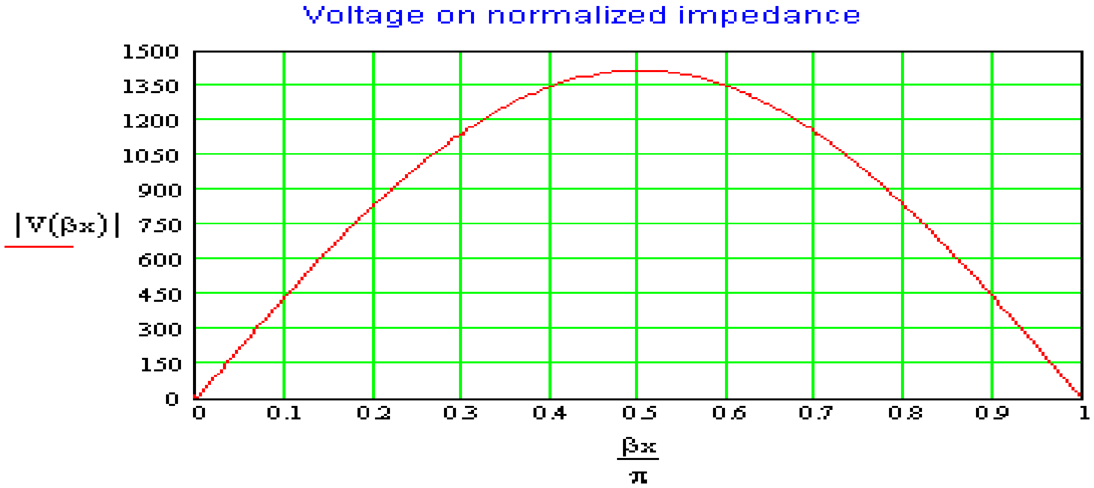
First we check the voltage on coupler (on normalized impedance) at 250 kW for different loads and without 3-stub transformer.



For variables:

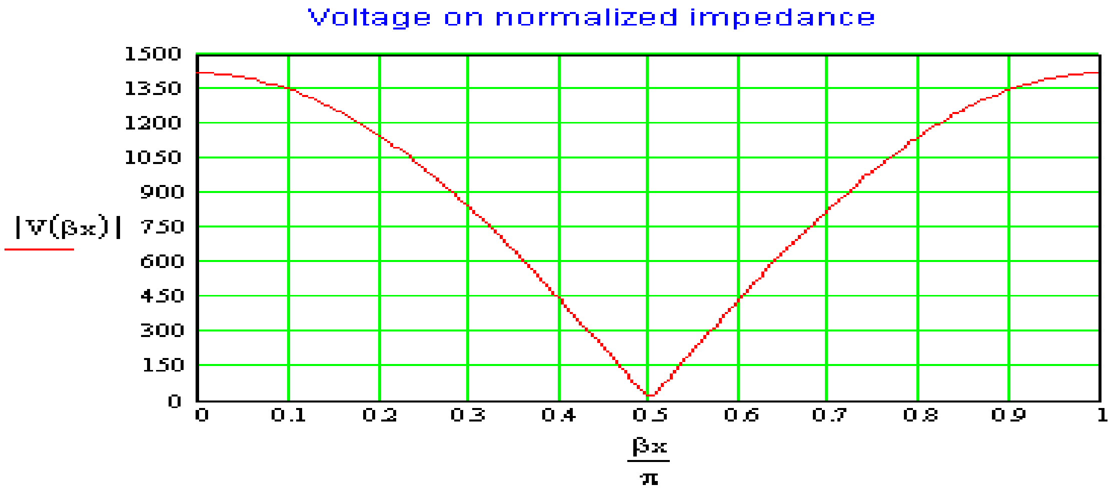
$P_G = 2.5 \times 10^5$ $\quad Q_{ext0} = 3.3 \times 10^6$ $\quad Q_{ext} = 3.3 \times 10^6$ $\quad R_G = 1$ $\quad R_L = 1$

Operation of coupler with fixed antenna and 3 stub tuner - model



For variables:

$P_G = 2.5 \times 10^5$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 3.3 \times 10^6$ $R_G = 1$ $R_L = 0$

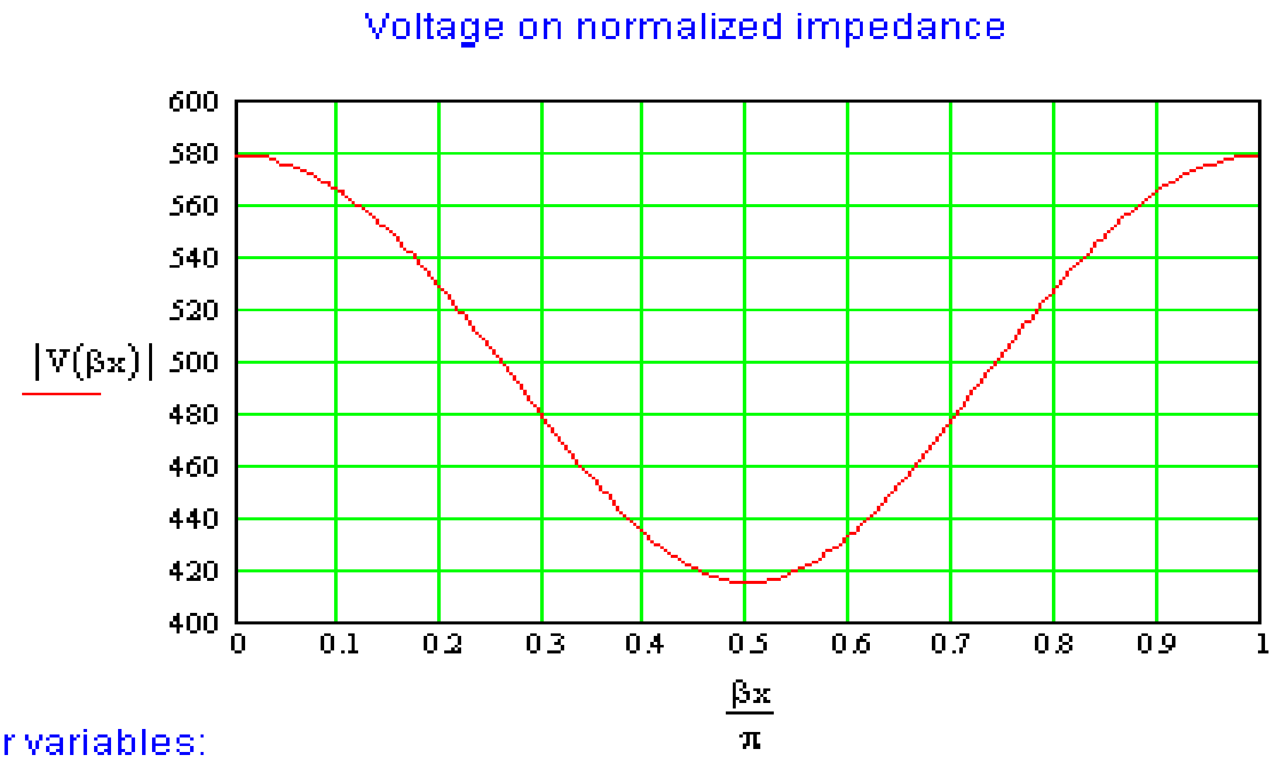


For variables:

$P_G = 2.5 \times 10^5$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 3.3 \times 10^6$ $R_G = 1$ $R_L = 1 \times 10^{307}$

Operation of coupler with fixed antenna and 3 stub tuner - model

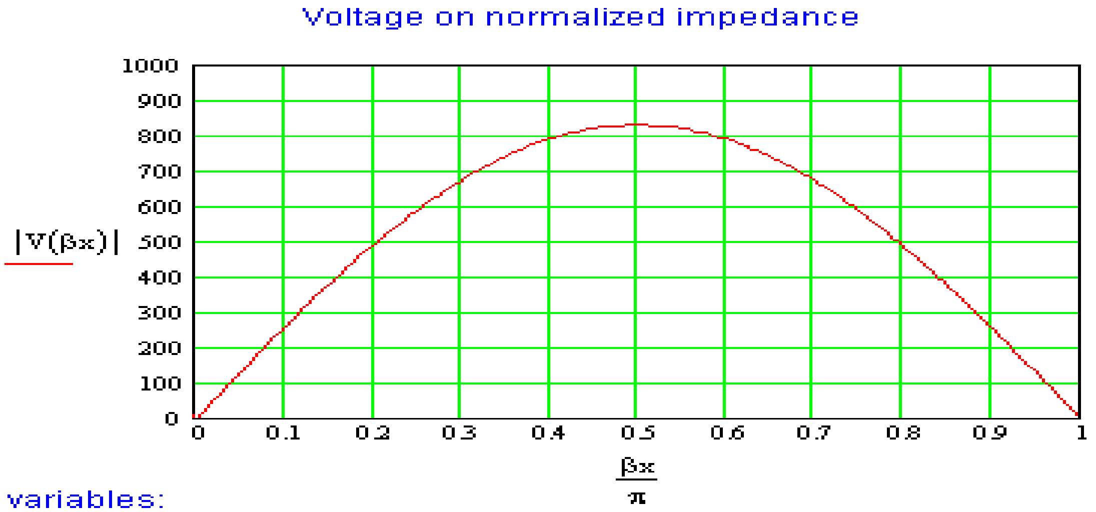
Now we check the voltage on the coupler with 3-stub transformer under given conditions of XFEL operation. First without energy recovery.



For variables:

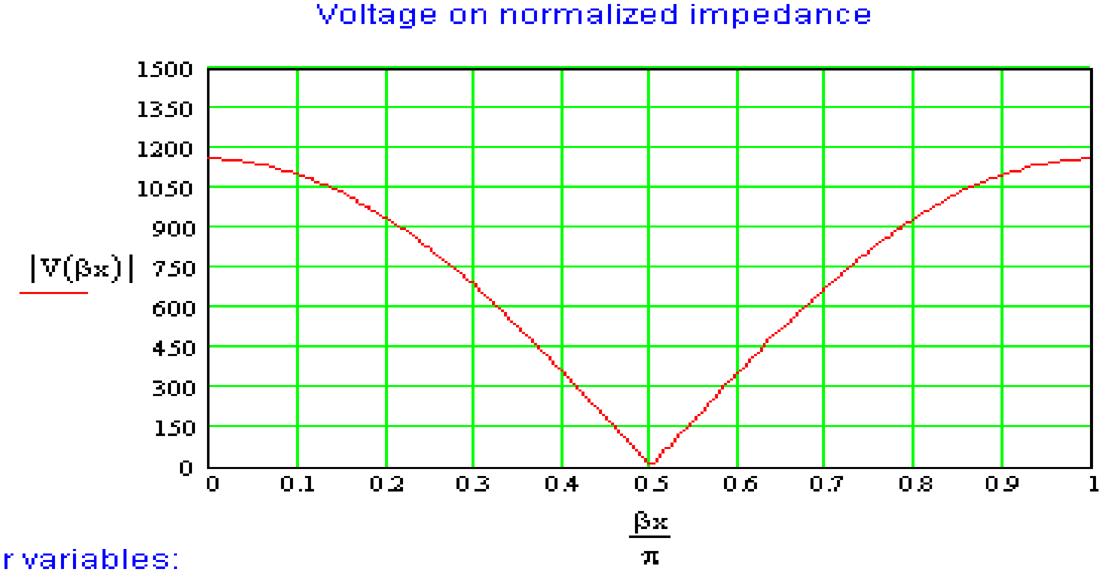
$P_G = 1.2 \times 10^5$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 4.6 \times 10^6$ $R_G = 1.394$ $R_L = 1.394$

Operation of coupler with fixed antenna and 3 stub tuner - model



For variables:

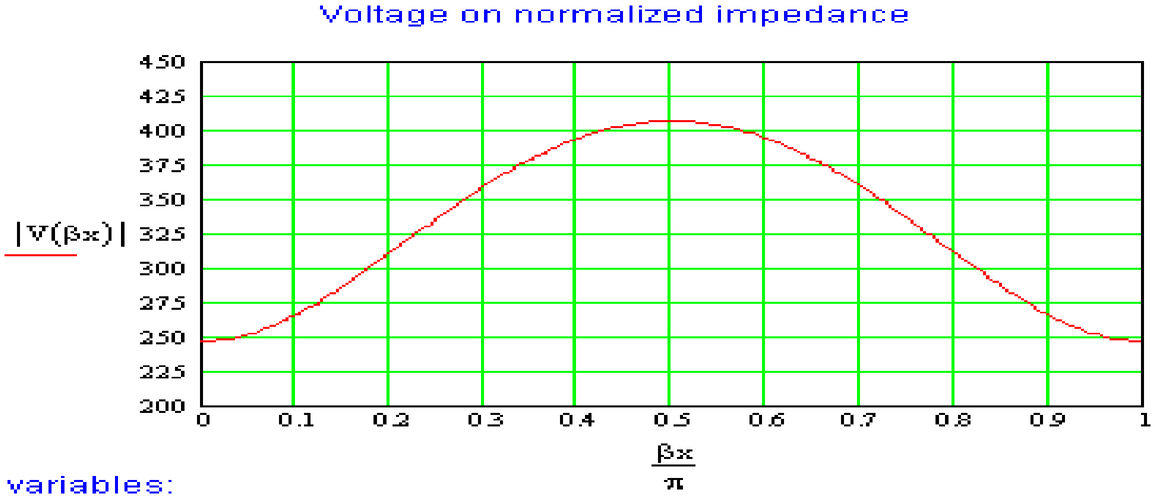
$P_G = 1.2 \times 10^5$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 4.6 \times 10^6$ $R_G = 1.394$ $R_L = 0$



For variables:

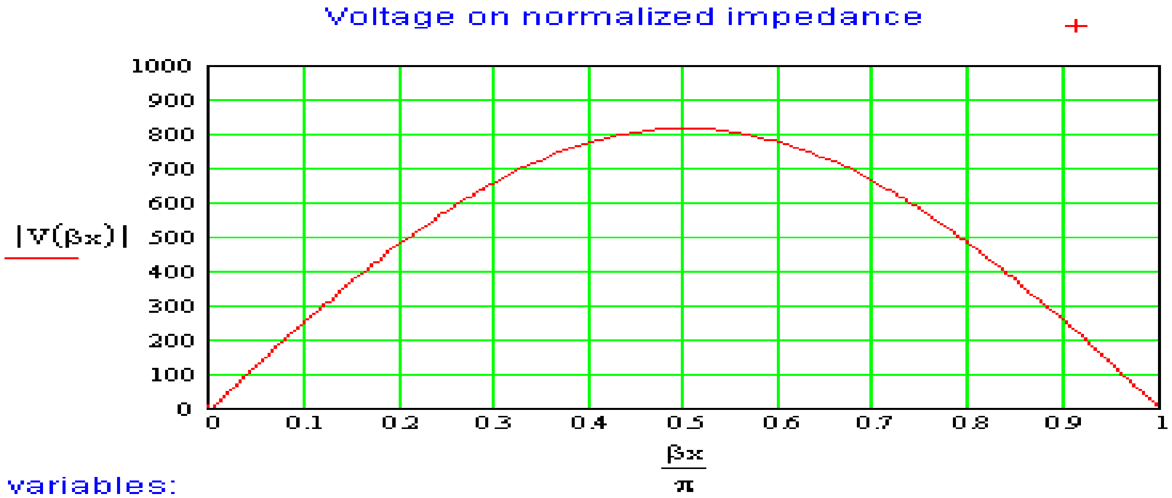
$P_G = 1.2 \times 10^5$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 4.6 \times 10^6$ $R_G = 1.394$ $R_L = 1 \times 10^6$

Operation of coupler with fixed antenna and 3 stub tuner - model



For variables:

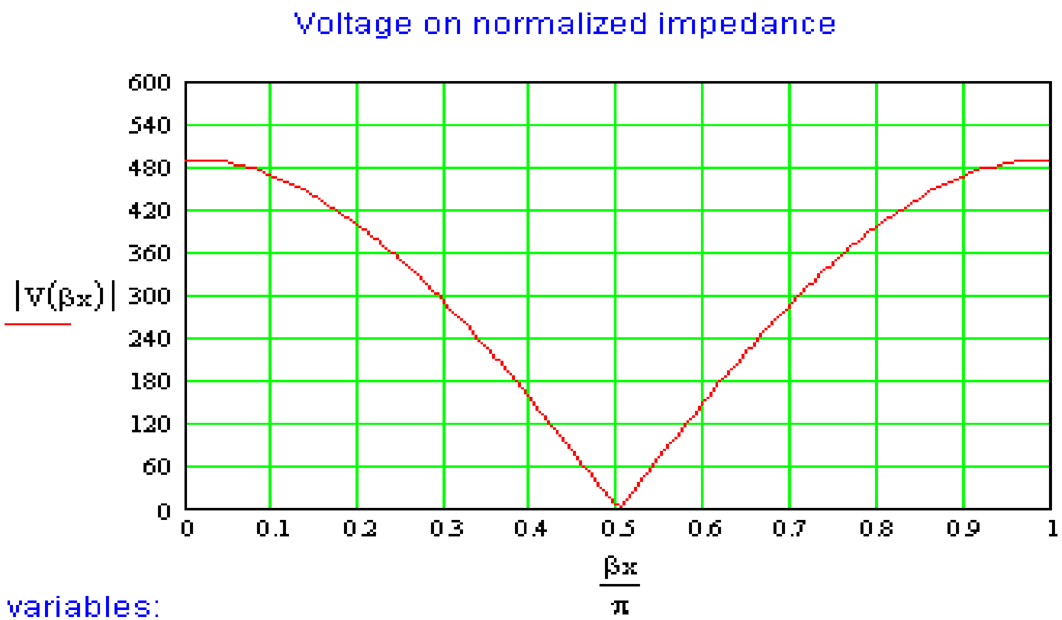
$P_G = 5 \times 10^4$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 2 \times 10^6$ $R_G = 0.606$ $R_L = 0.606$



For variables:

$P_G = 5 \times 10^4$ $Q_{ext0} = 3.3 \times 10^6$ $Q_{ext} = 2 \times 10^6$ $R_G = 0.606$ $R_L = 0$

Operation of coupler with fixed antenna and 3 stub tuner - model

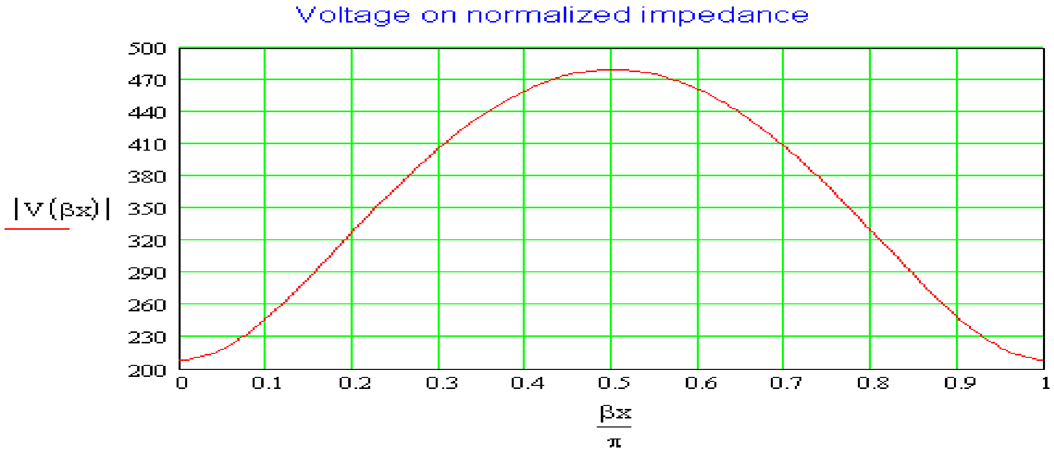


For variables:

$P_G = 5 \times 10^4$ $\quad Q_{ext0} = 3.3 \times 10^6$ $\quad Q_{ext} = 2 \times 10^6$ $\quad R_G = 0.606$ $\quad R_L = 1 \times 10^6$

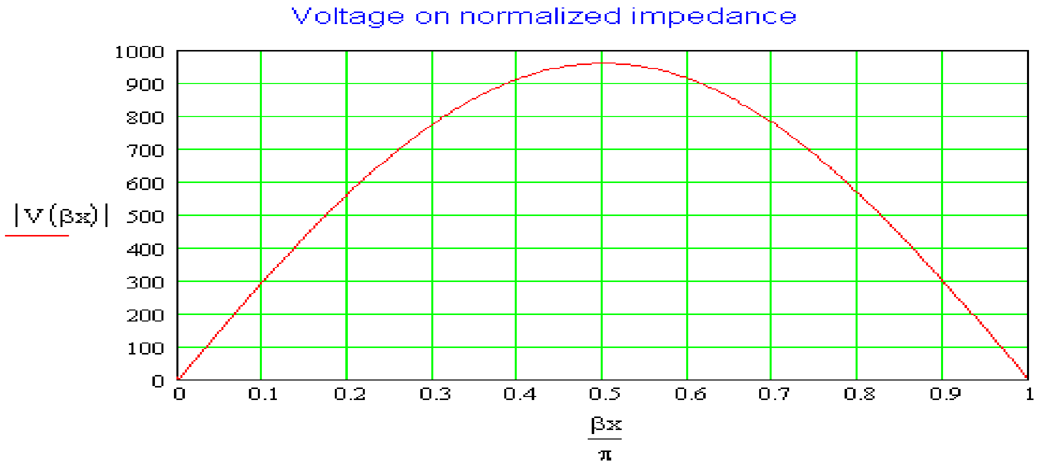
And now let's try to choose the coupler $Q_{ext} = 4{,}6.10^6$ and check tuning to $Q_{ext} = 2.10^6$ (min. Q without ER) and $1{,}5.10^7$ (max. Q with ER).

Operation of coupler with fixed antenna and 3 stub tuner - model



For variables:

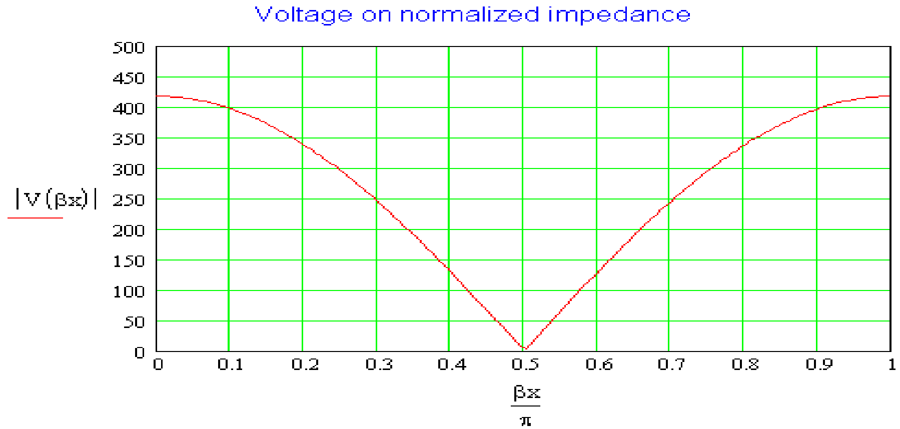
$P_G = 5 \times 10^4$ $Q_{ext0} = 4.6 \times 10^6$ $Q_{ext} = 2 \times 10^6$ $R_G = 0.435 R_L = 0.435$



For variables:

$P_G = 5 \times 10^4$ $Q_{ext0} = 4.6 \times 10^6$ $Q_{ext} = 2 \times 10^6$ $R_G = 0.435 R_L = 0$

Operation of coupler with fixed antenna and 3 stub tuner - model



For variables:

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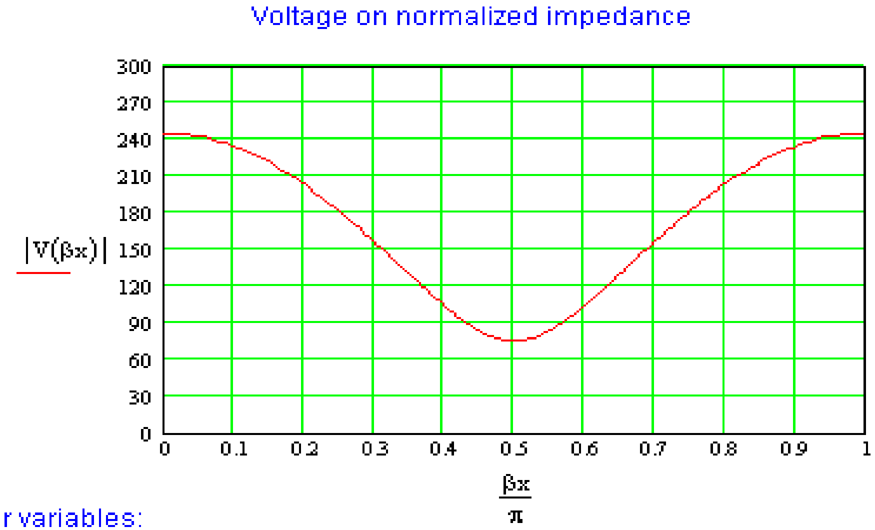
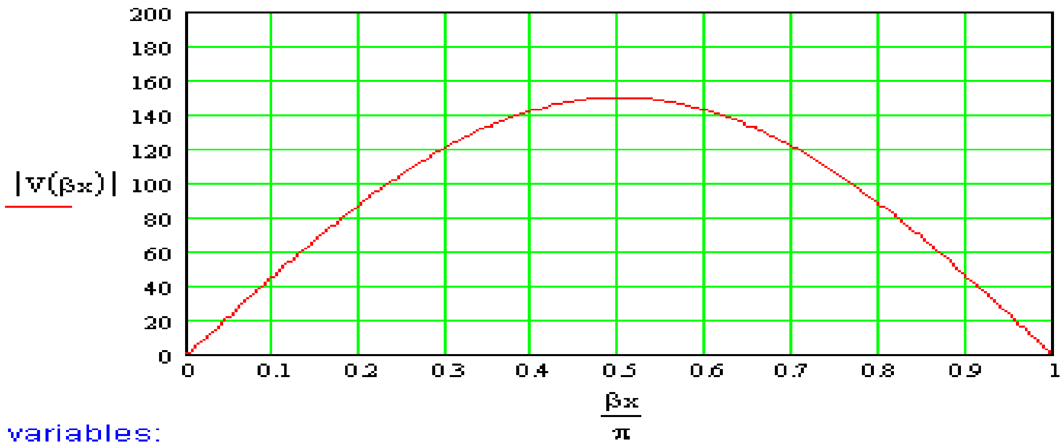


For variables:

$P_G = 9.2 \times 10^3$ $Q_{ext0} = 4.6 \times 10^6$ $Q_{ext} = 1.5 \times 10^7$ $R_G = 3.261$ $R_L = 3.261$

Operation of coupler with fixed antenna and 3 stub tuner - model

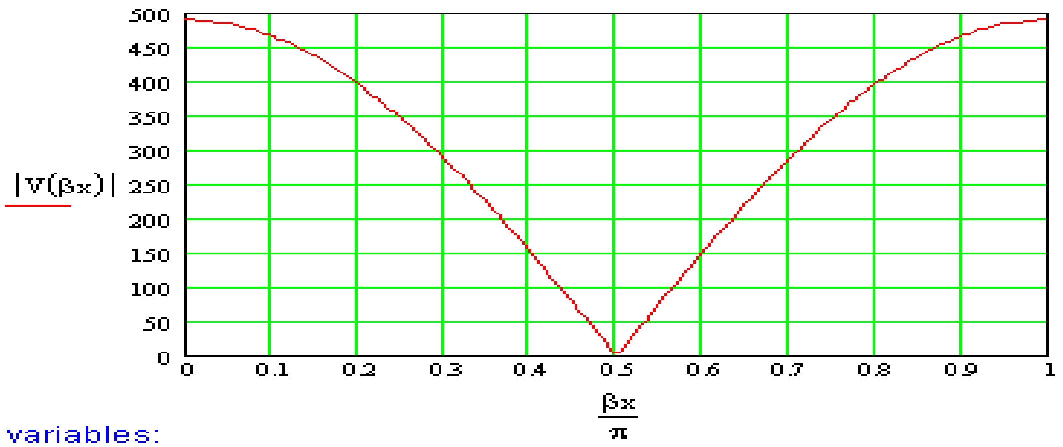
Voltage on normalized impedance



For variables:

$P_G = 9.2 \times 10^3$ $Q_{ext0} = 4.6 \times 10^6$ $Q_{ext} = 1.5 \times 10^7$ $R_G = 3.261$ $R_L = 0$

Voltage on normalized impedance



For variables:

$P_G = 9.2 \times 10^3$ $Q_{ext0} = 4.6 \times 10^6$ $Q_{ext} = 1.5 \times 10^7$ $R_G = 3.261$ $R_L = 1 \times 10^6$

Operation of coupler with fixed antenna and 3 stub tuner - conclusion

- Operation without ER:

  If the fixed Q_{ext} of coupler is chosen to $3{,}3.10^6$ and varied from 2.10^6 to $4{,}6.10^6$, the nominal voltage of coupler (1,41kV on normalized impedance) is never reached

- Operation with and without ER:

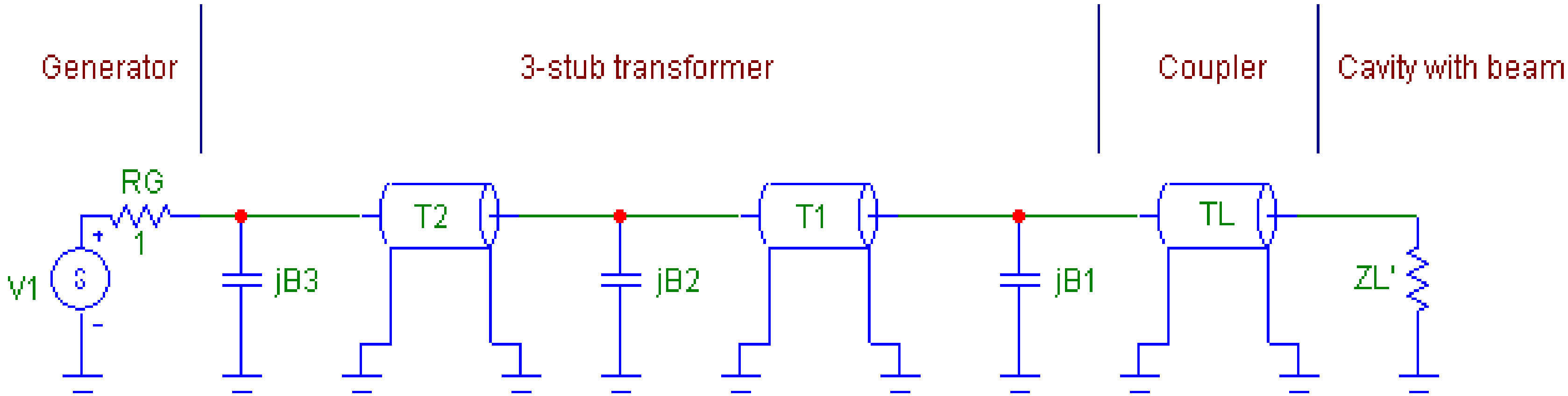
  If the fixed Q_{ext} of coupler is chosen to $4{,}6.10^6$ and varied from 2.10^6 to $1{,}5.10^7$, the nominal voltage of coupler is never reached

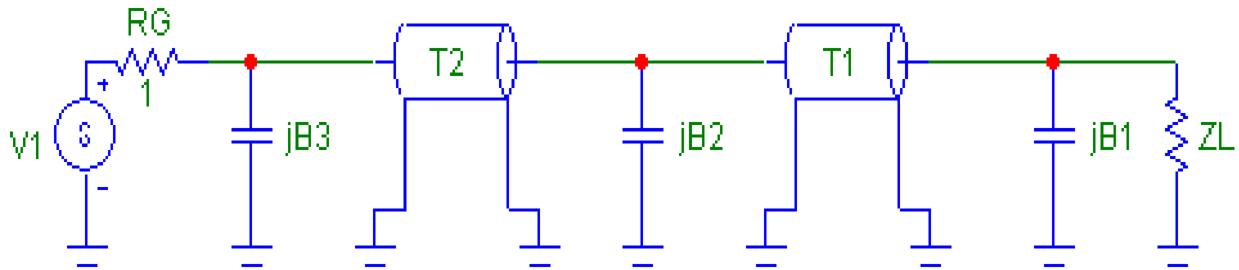
Range of phase shift of 3-stub transformer

- The previous analysis shows, that the use of 3-stub transformer for Q adjustment will not introduce unacceptable electric field enhancement
- Except Q adjustment the 3-stub transformer is also used for the phase correction, so we must check the range of possible phase shift when matching different loads
- This analysis is not possible in general, because the waveguide transformer has too much free parameters. We will analyze the most simple model consisting of pieces of transmission line and parallel capacities. This model is good for the waveguide transformer in case of thin stubs and not deep penetration.

Range of phase shift of 3-stub transformer

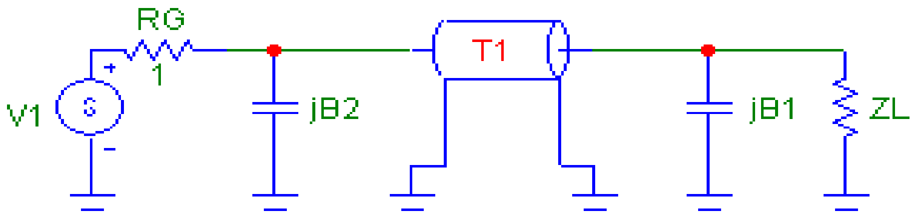
Model of 3-stub transformer with generator and cavity:





Range of phase shift of 3-stub transformer

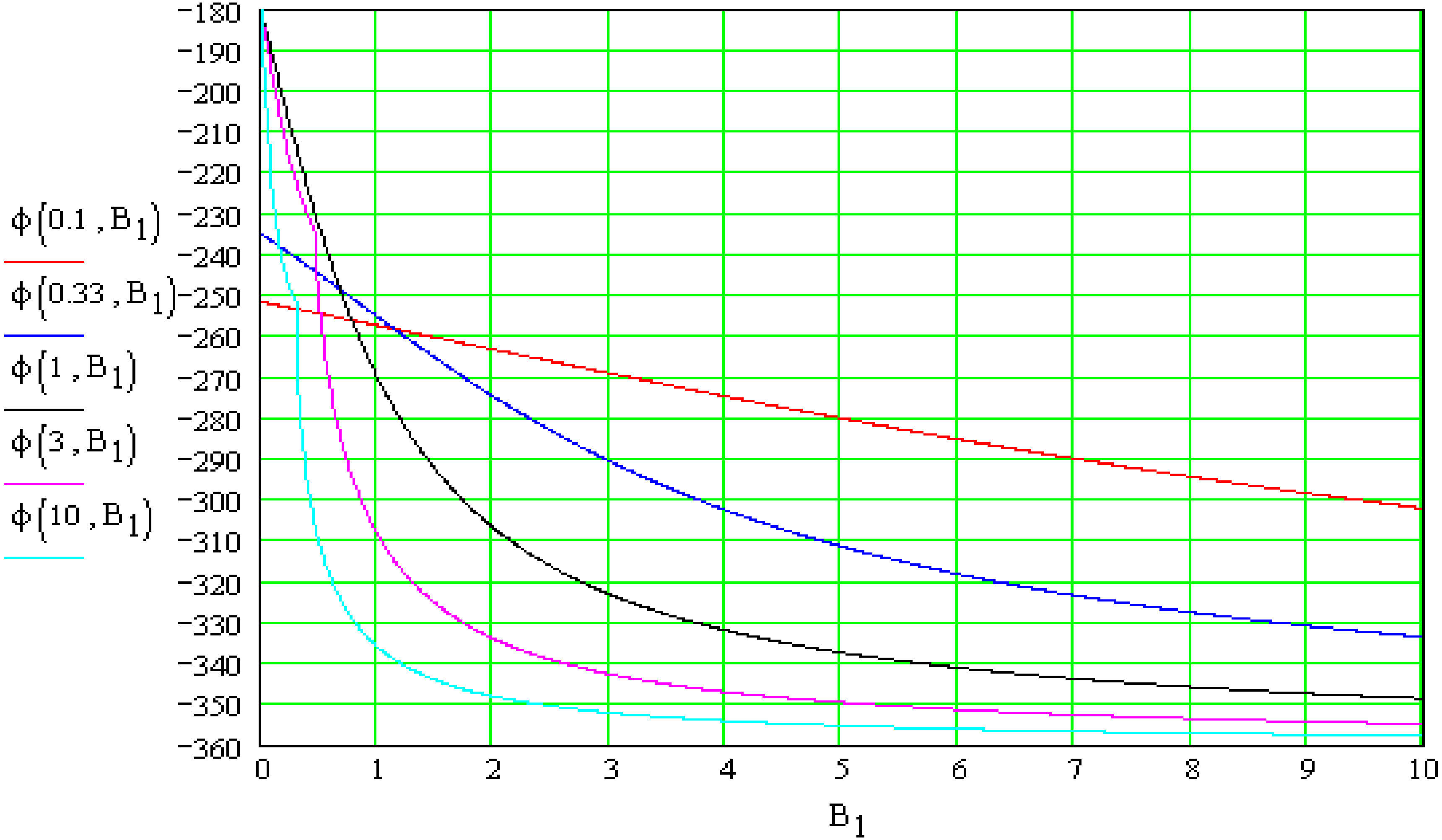
The principle of the 3-stub transformer is based on the principle of the 2-stub transformer:



- The admitance B1 has a value just to get normalized impedance 1-jB2 on the left side of transmission line. This has two solution, one capacitive (only this we will assume for the waveguide transformer) and one inductive.
- The admitance B2 compensates the reactive part of this impedance
- This problem has no solution for $G_L > \sin^{-2}(\beta l)$, where l is the length of the line. To overcome this, a third stub is used to transform the load impedance to the operational region of the 2-stub transformer.
- Now the problem has an infinite number of solutions, which give us freedom to control the phase shift

Range of phase shift of 3-stub transformer

Stub distance = λ/4, (βl = π/2)



Range of phase shift of 3-stub transformer - conclusion

- The best distance between stubs for impedance matching and phase shifting is $\lambda/4$
- The phase shift range for different load resistances are:

R_L [norm]	ϕ_{min} [°]	ϕ_{max} [°]	$\Delta\phi$ [°]
0.1	-250	-300	50
0.33	-235	-335	100
1	-180	-350	170
3	-235	-350	115
10	-250	-355	105

- For all operation conditions of linac (without or with ER) we have the range at least 100°
- In case of real waveguide 3-stub transformer this analysis must be done with more precise model in parallel with design